THE GEORGE WASHINGTON UNIVERSITY
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HPCL The George Washington University WASHINGTON DC
High Performance Computing Lab

Performance Scalability of a Remote Sensing Application on High Performance Reconfigurable Platforms

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Outline

- Objective
- Motivations
- Cloud Detection and Landsat 7 ACCA
- Implementation Approach
- Experimental Results
- Concluding Remarks

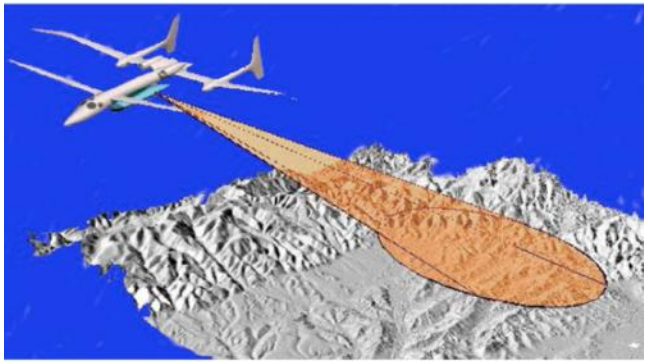
Objective

- Proof of concept for an onboard system for cloud detection using High Performance Reconfigurable Computers (HPRCs)

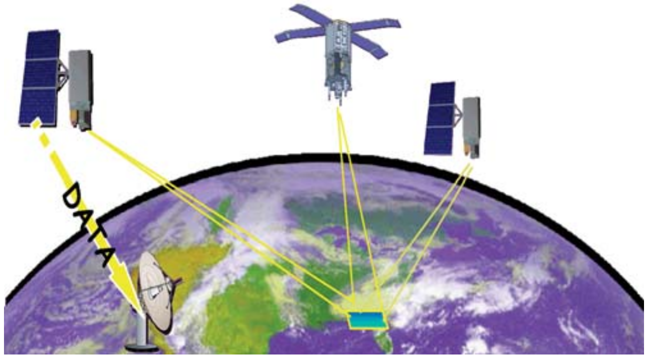
- Targets Landsat 7 ETM+ and ACCA algorithm to:
  - Determine an almost practical bounds on the potential performance of HPRCs
  - Gain an insight into the system level programmability and performance issues

Motivations

- **Why Cloud Detection?**
  - **Can render data useless in land-use/land cover studies**
  - **Critical in weather and climate studies**
- **Why On-Board ?**
  - **Reduction of communication bandwidth**
  - **Reduce cost and complexity of ground processing systems**
  - **Enable autonomous decisions**
- **Why Reconfigurable?**
  - **Flexibility is Important for Space**
  - **High Performance, ..**



Airborne



Spaceborne

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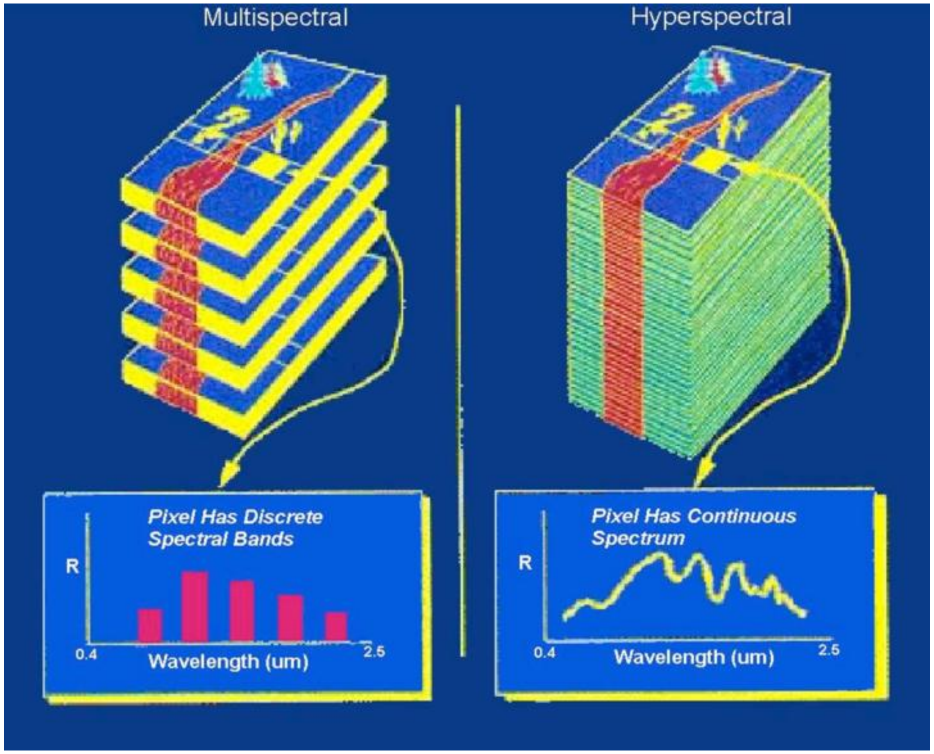
Remote Sensing

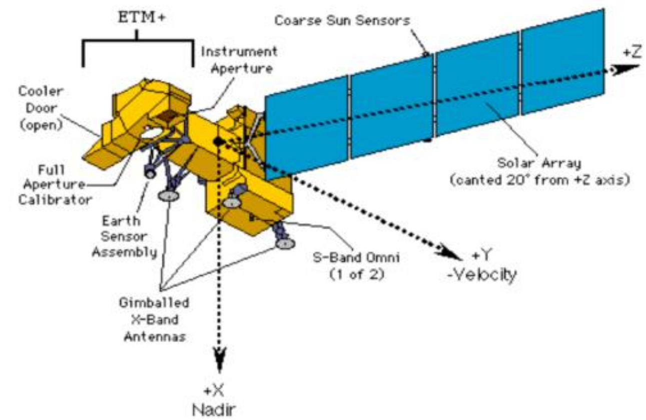
- **Multi-Spectral Imagery**
  - A few to 10's of bands (**LANDSAT ≡ 8 bands**, MODIS ≡ 36 bands, SeaWiFS ≡ 8 bands, IKONOS ≡ 5 bands)
- **Hyperspectral Imagery**
  - 100's-1000's of bands (AVIRIS ≡ 224 bands, AIRS ≡ 2378 bands)



Multispectral / Hyperspectral Imagery Comparison

Landsat 7 AND Cloud Detection

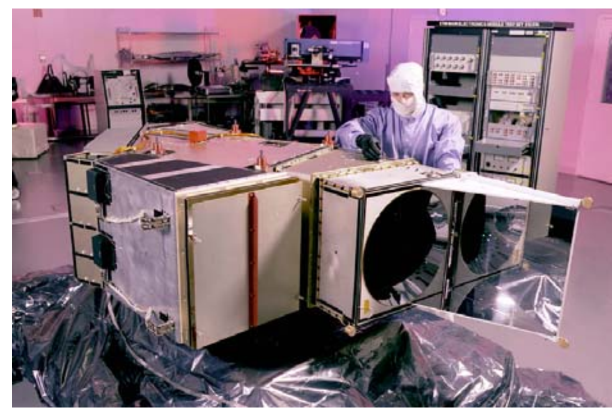
- **ACCA (Automatic Cloud Cover Assessment) for Landsat 7 ETM+**
  - **ETM+ has 8 bands**
  - **ACCA algorithm uses Band2- Band6**
  - **Threshold based - 8 filters (tests)**
  - **Three-Step approach**



Landsat 7

Landsat 7 Quantized Raw Data

Calibration Constants → **Normalization** → **Pass One** → **Pass Two**



ETM+

Cloud Detection Theory

- **Idea is based on the observation that clouds are Highly Reflective and Cold:**
  - **Highly reflective (in the visible, near- and mid- IR bands)**
    - **Visible Bands**
      - Green band (Band2 ≡ 0.52 - 0.60 μm)
        - Measures green reflectance → Vegetation discrimination
      - Red band (Band3 ≡ 0.63 - 0.69 μm)
        - Measures Chlorophyll absorption → Plant Species differentiation
        - Combined with Green Band shows land surface as red-like

Cloud Detection Theory (cnt'd)

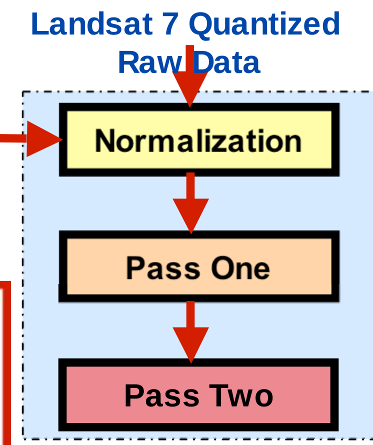
- **Near-IR Band (Band4 ≡ 0.76 - 0.90 μm)**
  - Determines soil moisture level → Delineating water bodies and distinguishing vegetation types
- **Mid-IR Band (Band5 ≡ 1.55 - 1.75 μm)**
  - Differentiation of snow from clouds

0 **Cold (in the thermal bands)**

- **Thermal IR Band (Band6 ≡ 10.4 - 12.5 μm)**
  - Thermal mapping to Brightness Temperatures
  - Difference between 11 μm & 12 μm highlights cloud boundaries

Landsat 7 ETM+ ACCA
(Algorithm Outline)

- **Normalization**
  - Bands 2-5 (Reflectance bands)
  - Band 6 (Thermal band)
    - Calibrated to blackbody Brightness Temperature



Calibration Constants

ETM+ Spectral Radiance Range
watts/(meter squared * ster * µm)

Band Number	Before July 1, 2000				After July 1, 2000			
	Low Gain		High Gain		Low Gain		High Gain	
	LMIN	LMAX	LMIN	LMAX	LMIN	LMAX	LMIN	LMAX
1	-6.2	297.5	-6.2	194.3	-6.2	293.7	-6.2	191.6
2	-6.0	303.4	-6.0	202.4	-6.4	300.9	-6.4	196.5
3	-4.5	235.5	-4.5	158.6	-5.0	234.4	-5.0	152.9
4	-4.5	235.0	-4.5	157.5	-5.1	241.1	-5.1	157.4
5	-1.0	47.70	-1.0	31.76	-1.0	47.57	-1.0	31.06
6	0.0	17.04	3.2	12.65	0.0	17.04	3.2	12.65
7	-0.35	16.60	-0.35	10.932	-0.35	16.54	-0.35	10.80
8	-5.0	244.00	-5.0	158.40	-4.7	243.1	-4.7	158.3

ETM+ Solar Spectral Irradiances

Band	watts/(meter squared * µm)
1	1969.000
2	1840.000
3	1551.000
4	1044.000
5	225.700
7	82.07
8	1368.000

Earth-Sun Distance in Astronomical Units

Julian Day	Distance	Julian Day	Distance	Julian Day	Distance	Julian Day	Distance	Julian Day	Distance
1	.9832	74	.9945	152	1.0140	227	1.0128	305	.9925
15	.9836	91	.9993	166	1.0158	242	1.0092	319	.9892
32	.9853	106	1.0033	182	1.0167	258	1.0057	335	.9860
46	.9878	121	1.0076	196	1.0165	274	1.0011	349	.9843
60	.9909	135	1.0109	213	1.0149	288	.9972	365	.9833

ETM+ Thermal Band Calibration Constants

	Constant 1 - K1 watts/(meter squared * ster * µm)	Constant 2 - K2 Kelvin
Landsat 7	666.09	1282.71

Landsat 7 ETM+ ACCA
(Algorithm Outline)

- **Normalization**
  - Extract the calibration constants ($L_{MIN\lambda}$, $L_{MAX\lambda}$, d, $E_{SUN\lambda}$, θ_s, K_1, K_2) from the tables depending on the information in the data file headers
  - Calculate radiance (L_λ) for captured data
  - Calculate reflectance (ρ) for band 2-5
  - Calculate temperature (T) for band 6 only
- **Reflectance is a linear function of the raw quantized data (Q_{cal})**
- **Temperature is a non-linear function of the raw data**

$$L_{\lambda_i} = \left(\frac{L_{\max_{\lambda_i}} - L_{\min_{\lambda_i}}}{Q_{cal_{\max}} - Q_{cal_{\min}}} \right) \left(Q_{cal_i} - Q_{cal_{\min}} \right) + L_{\min_{\lambda_i}}$$

$$\forall\ i \in \{2,3,4,5,6\}$$

$$\rho_{p_i} = \frac{\pi \cdot d^2}{E_{sun_{\lambda_i}} \cos(\theta_s)} \cdot L_{\lambda_i} \ , \ \forall\ i \in \{2,3,4,5\}$$

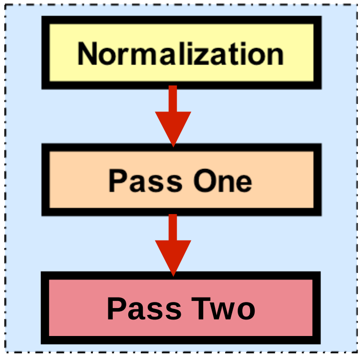
$$\rho_{p_i} = \beta_i \cdot Q_{cal_i} + \alpha_i \ , \ \forall\ i \in \{2,3,4,5\}$$

$$T = \frac{K_2}{\ln\left(\frac{K_1}{L_{\lambda_i}} + 1 \right)} \ , \ i = 6$$

Landsat 7 ETM+ ACCA
(Algorithm Outline)

◆ Pass One

- **Identifies clouds (produces Cloud Mask)**
- **Minimizes errors of commission**



	Filter	Function
1	**Brightness Threshold** $B_3 > 0.08$	Eliminates dark images
2	**Normalized Difference Snow Index (NDSI)** $NDSI = \frac{B_2 - B_5}{B_2 + B_5} < 0.7$	Eliminates many types of snow
3	**Temperature Threshold** $B_6 < 300K$	Eliminates warm image features
4	**Band 5/6 Composite** $(1 - B_5)B_6 < 225$	Eliminates numerous categories including ice
5	**Band 4/3 ratio** $\frac{B_4}{B_3} < 2$	Eliminates bright vegetation and soil
6	**Band 4/2 ratio** $\frac{B_4}{B_2} < 2$	Eliminates ambiguous features
7	**Band 4/5 ratio** $\frac{B_4}{B_5} > 1$	Eliminates rocks and desert
8	**Band 5/6 Composite** $(1 - B_5)B_6 > 210 \Rightarrow warm\ clouds$ $(1 - B_5)B_6 < 210 \Rightarrow cold\ clouds$	Distinguishes warm clouds from cold clouds

Landsat 7 ETM+ ACCA
(Algorithm Outline)

Classification	Rule
Snow	$\left(NSDI = \frac{B_2 - B_5}{B_2 + B_5} > 0.7\right)\ AND\ (B_4 > 0.1)^A$
Desert	$\frac{B_4}{B_5} < 0.83^B$
NotCloud	$(B_3 < 0.08)\ OR\ (B_6 > 300)\ OR\ (Snow)$
Ambiguous	$\left(((1-B_5)B_6 > 225)\ OR\ \left(\frac{B_4}{B_3} > 2\right)\ OR\ \left(\frac{B_4}{B_2} > 2\right)\ OR\ (Desert)\right)\ AND\ (\sim NotCloud)$
ColdCloud	$((1-B_5)B_6 \geq 210)\ AND\ (\sim Ambiguous)\ AND\ (\sim NotCloud)$
WarmCloud	$((1-B_5)B_6 < 210)\ AND\ (\sim Ambiguous)\ AND\ (\sim NotCloud)$

Classification Rules for Pass One [2]

Landsat 7 ETM+ ACCA
(Algorithm Outline)

- **Pass Two**
  - **Defines ambiguous clouds**
    - **Thermal properties of clouds identified during Pass One are characterized and used to identify remaining cloud pixels**
    - **Band 6 statistical moments (mean, standard deviation, skew, kurtosis) are computed for clouds identified during Pass One**
    - **The 95th percentile becomes the new thermal threshold for Pass Two**
    - **Image pixels that fall below the new thermal threshold and survive the first three Pass-One filters are classified as clouds**

$$\eta = \frac{1}{n}\sum_{i=1}^{n} x_i \quad , \quad \sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \eta)^2$$

$$Skewness = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - \eta}{\sigma}\right)^3$$

$$Kurtosis = \frac{1}{n-3}\sum_{i=1}^{n}\left(\frac{x_i - \eta}{\sigma}\right)^4$$

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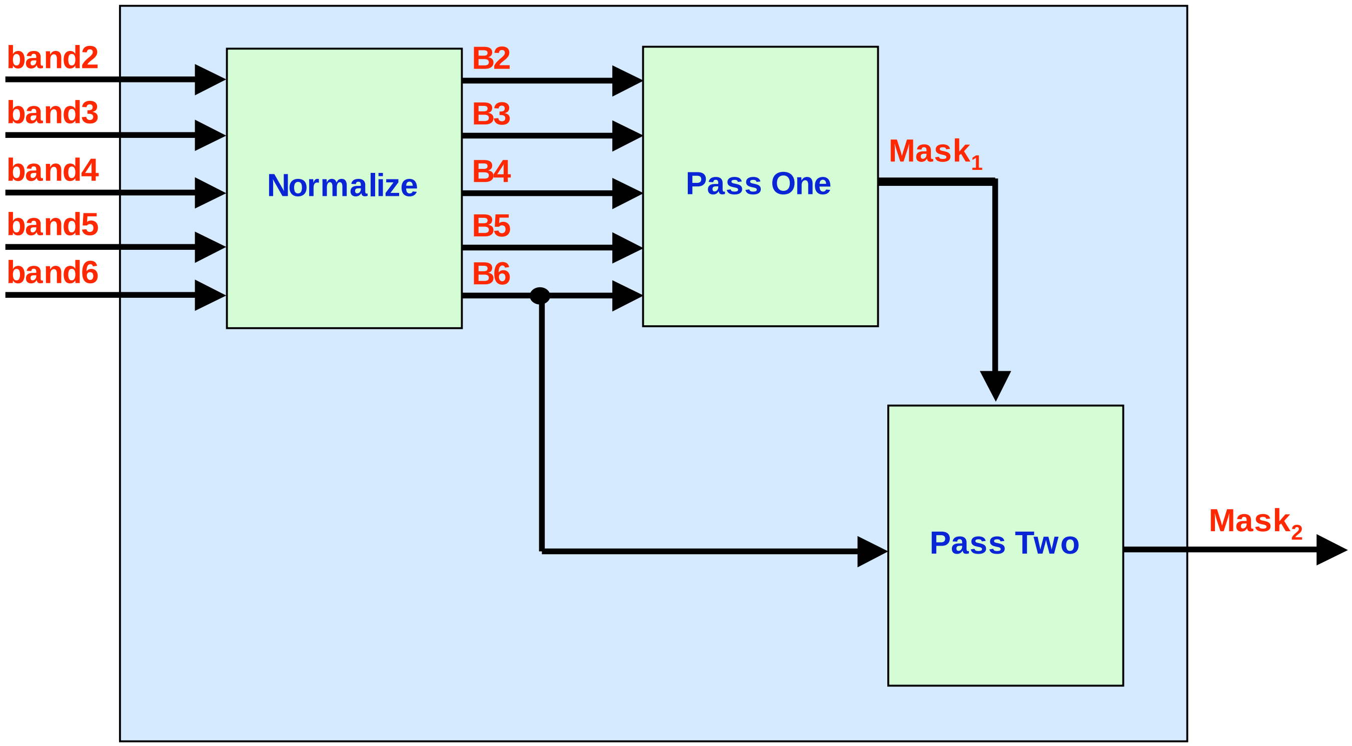
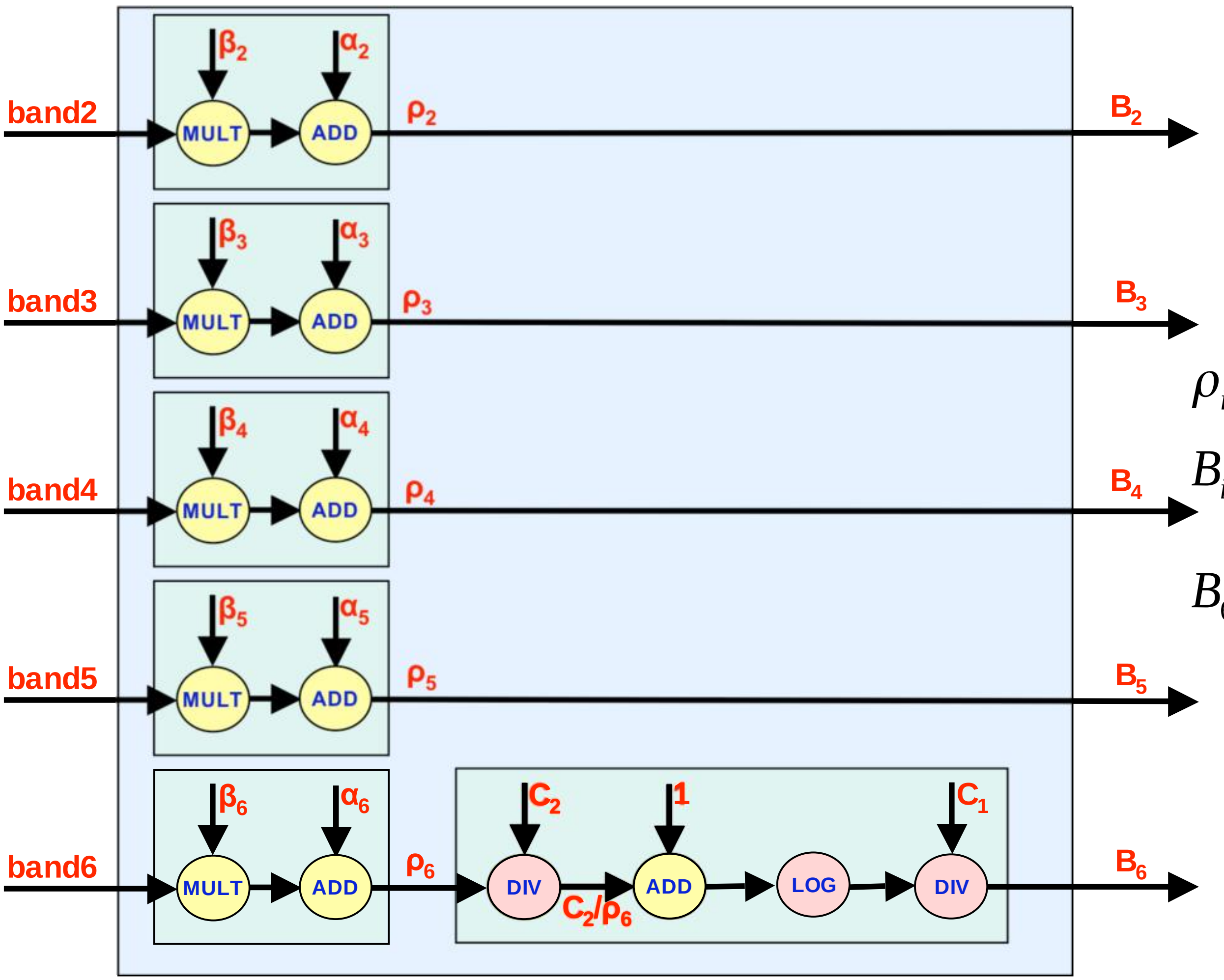
Top Hierarchy Module



Normalization Module

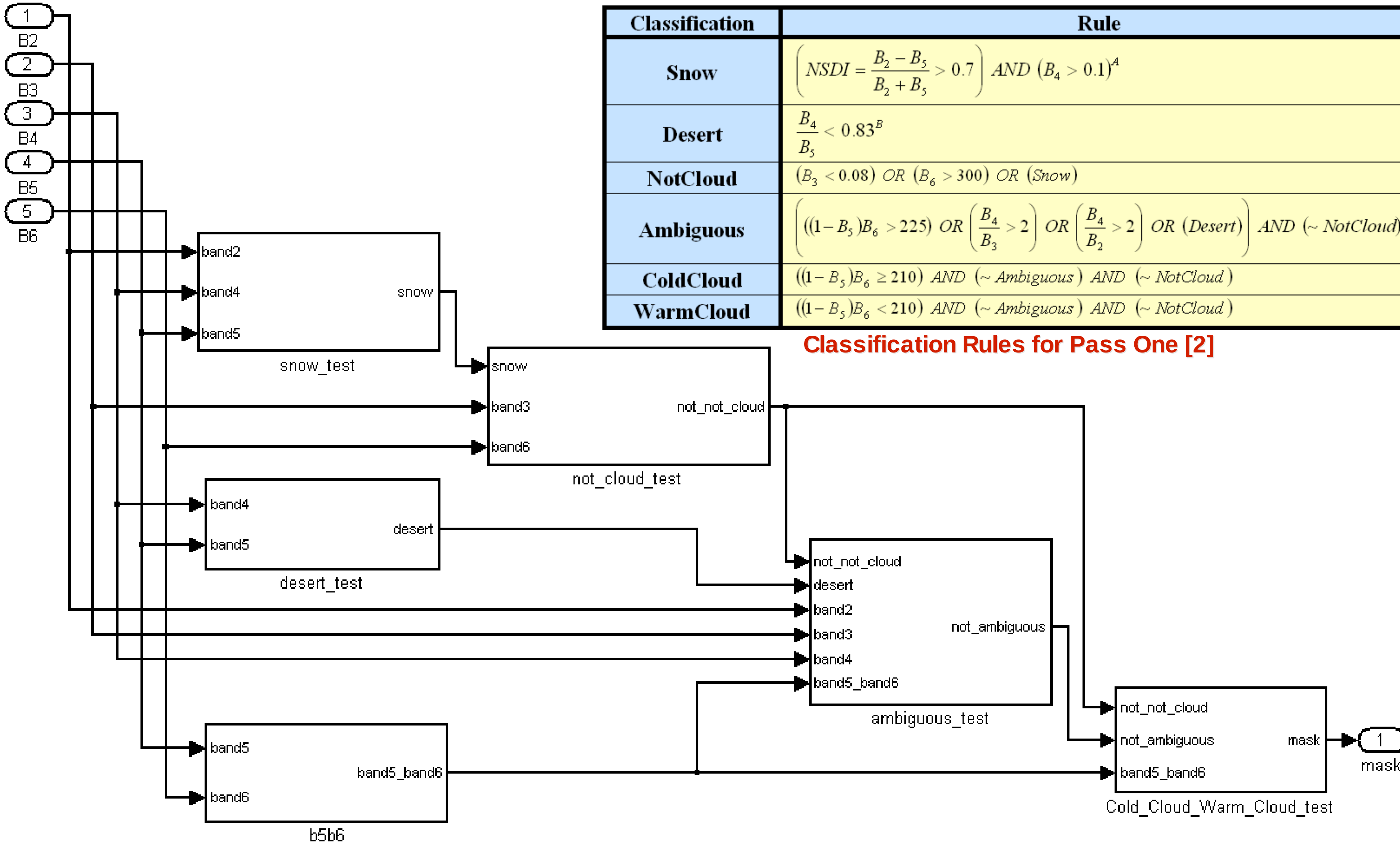


$$\rho_i = \beta_i \times band_i + \alpha_i \;,\; i = 2,3,4,5,6$$

$$B_i = \rho_i \;,\; i = 2,3,4,5$$

$$B_6 = \frac{K_2}{\ln\left(\frac{K_1}{\rho_6} + 1\right)}$$

Pass-One Module



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Desert	$\frac{B_4}{B_5} < 0.83^B$
NotCloud	$(B_3 < 0.08) \ OR \ (B_6 > 300) \ OR \ (Snow)$
Ambiguous	$\left(((1 - B_5)B_6 > 225) \ OR \left(\frac{B_4}{B_3} > 2 \right) OR \left(\frac{B_4}{B_2} > 2 \right) OR \ (Desert) \right) AND \ (\sim NotCloud)$
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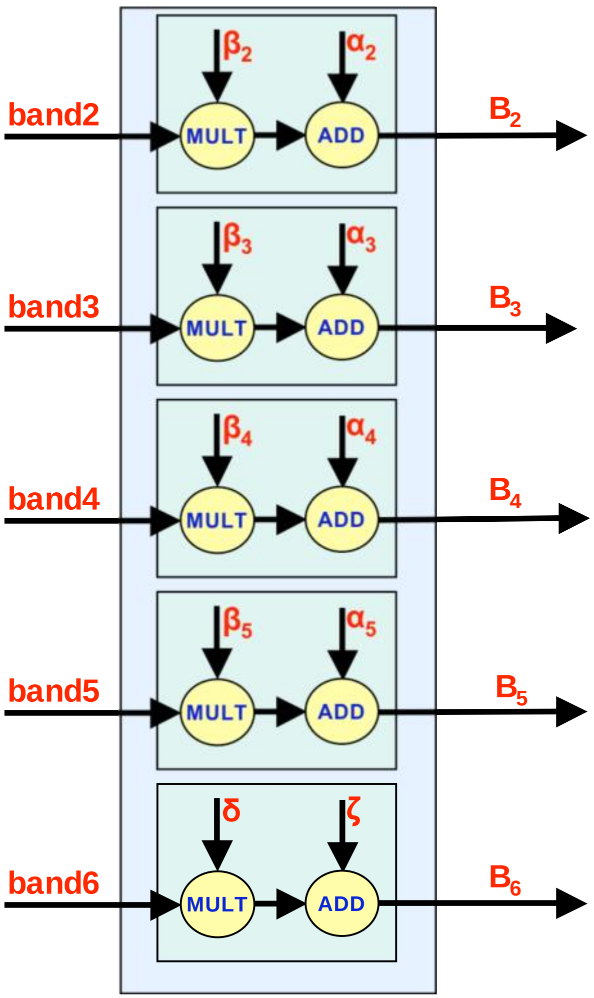
Classification Rules for Pass One [2]

Optimizing Hardware Resources Usage
(Linearization of the Normalization Function)



$$\rho_i = \beta_i \times band_i + \alpha_i \ , \ \ i = 2,3,4,5,6$$

$$B_i = \rho_i \ , \ \ i = 2,3,4,5$$

$$B_6 = \frac{K_2}{\ln\left(\frac{K_1}{\rho_6} + 1\right)} \cong \frac{K_2}{1 + \ln(K_1)} + \frac{K_2\left(1 - \frac{1}{K_1}\right)}{(1 + \ln(K_1))^2} \times \rho_6$$

$$B_6 \cong \left(\frac{K_2}{1 + \ln(K_1)} + \frac{K_2\left(1 - \frac{1}{K_1}\right) \cdot \alpha_6}{(1 + \ln(K_1))^2} \right) + \left(\frac{K_2\left(1 - \frac{1}{K_1}\right) \cdot \beta_6}{(1 + \ln(K_1))^2} \right) \times band_6$$

$$B_6 \cong \zeta + \delta \times band_6$$

Optimizing Hardware Resources Usage (cnt'd)

(Algebraic Re-Formulation of Pass-One Filters)

Classification	Rule
Snow	$\left(NSDI = \frac{B_2 - B_5}{B_2 + B_5} > 0.7\right)\ AND\ (B_4 > 0.1)^A$
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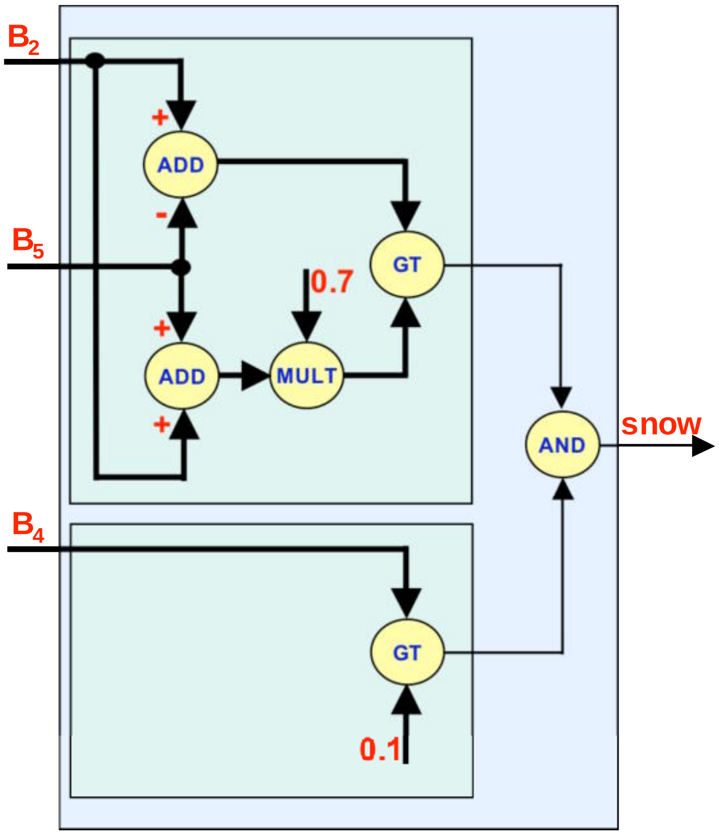
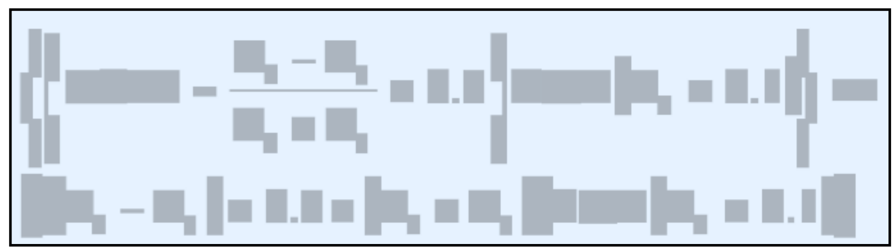


Snow-Test Module

Division Eliminated



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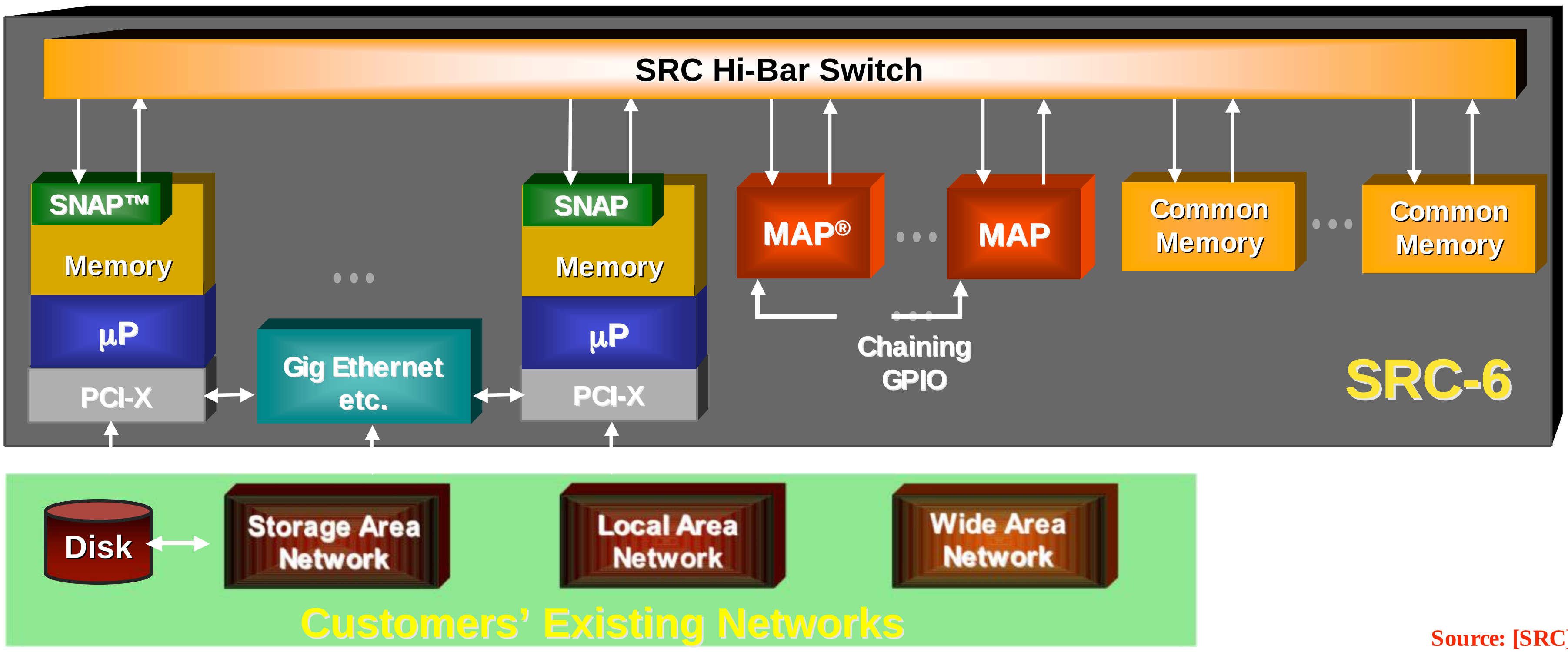
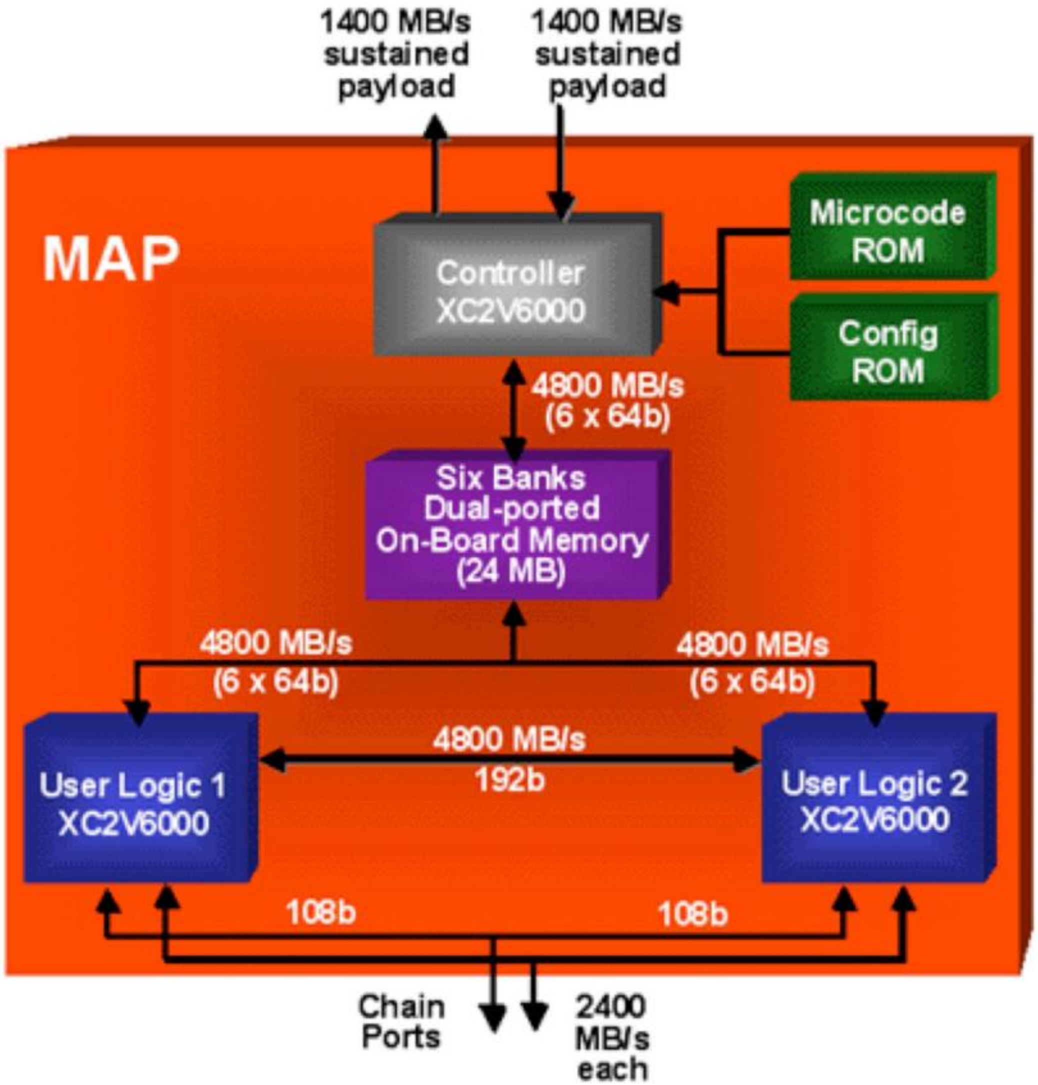
SRC Hi-Bar™ Based Systems

- Hi-Bar sustains 1.4 GB/s per port with 180 ns latency per tier
- Up to 256 input and 256 output ports with two tiers of switch
- Common Memory (CM) has controller with DMA capability
- Controller can perform other functions such as scatter/gather
- Up to 8 GB DDR SDRAM supported per CM node



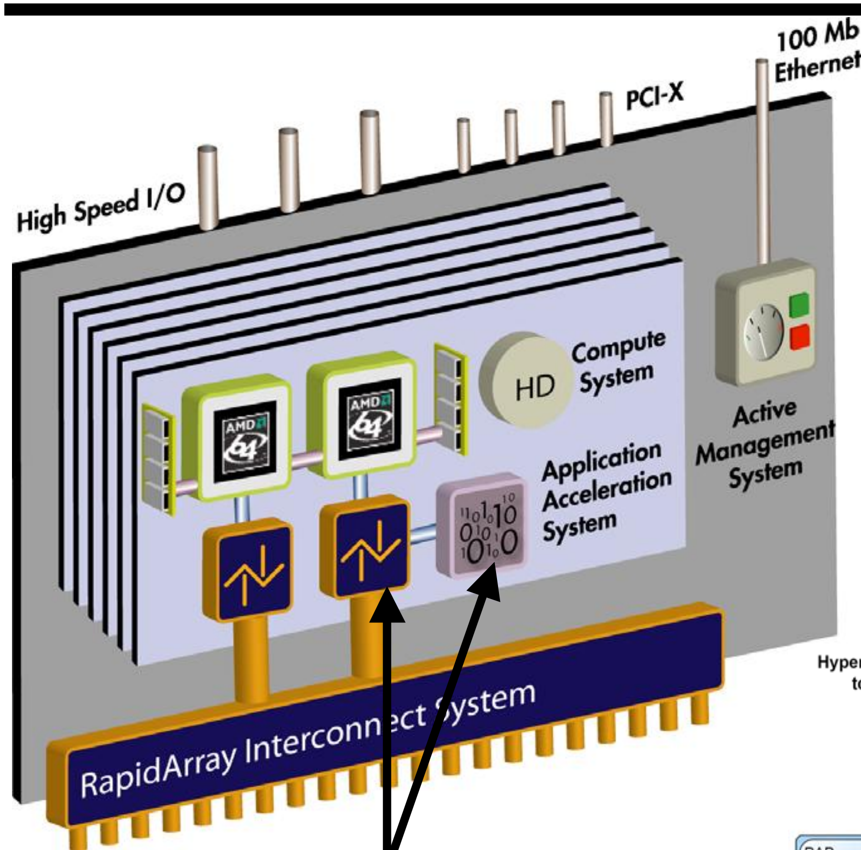
Source: [SRC]

SRC Reconfigurable Processor

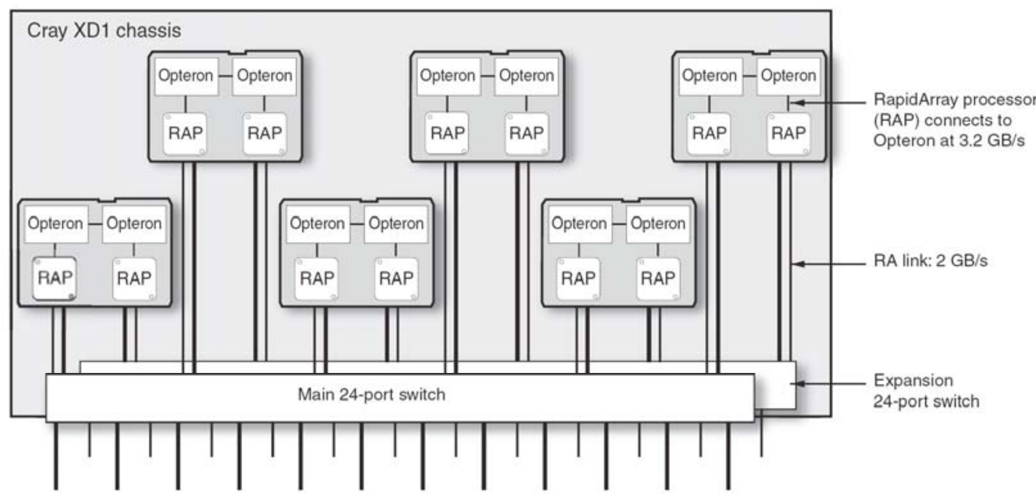


Source: [SRC]

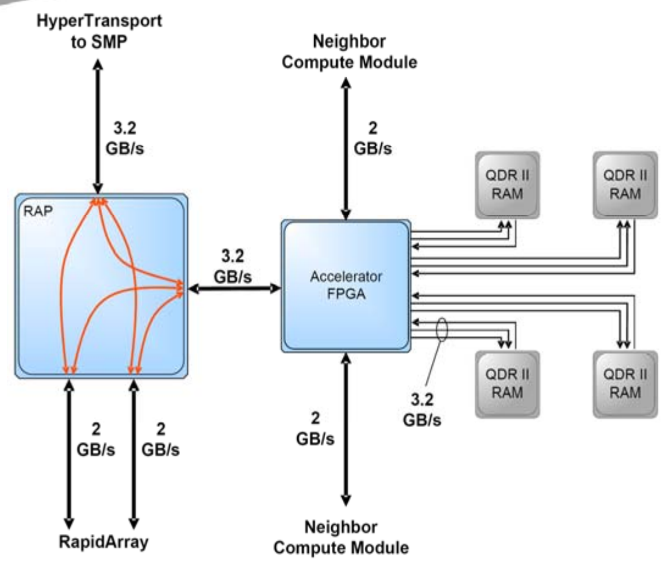
Cray XD1 System Architecture
(One Chassis)



FPGA and 2nd RAP are on Expansion Module



RapidArray components in a Cray XD1 chassis



Compute
- 12 AMD Opteron 32/64 bit, x86 processors
- High Performance Linux

RapidArray Interconnect
- 12 communications processors
- 1 Tb/s switch fabric

Active Management
- Dedicated processor

Application Acceleration
- 6 co-processors

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  - Detection Accuracy
  - Measurements
  - Performance
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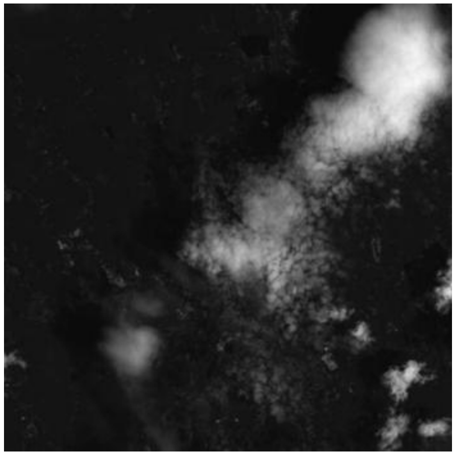
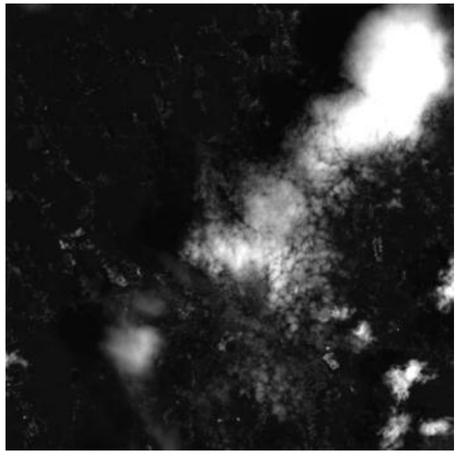
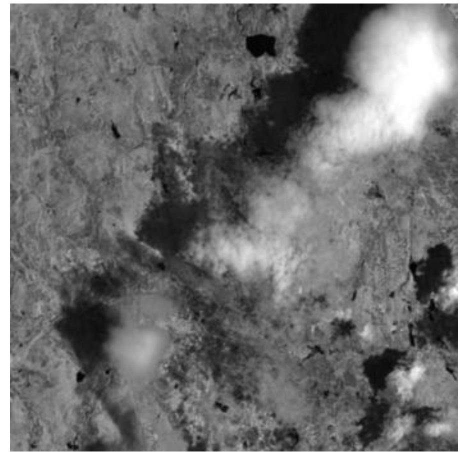
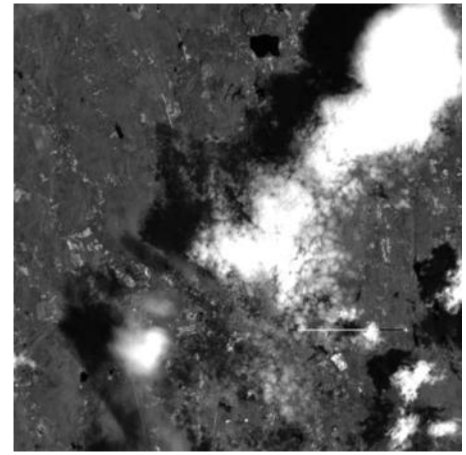
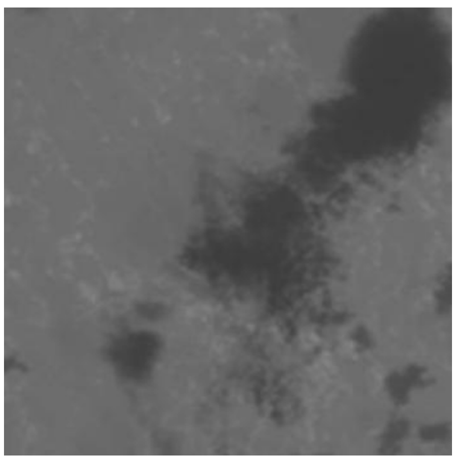
Detection Accuracy
(Software/Reference Mask, Hardware Masks)

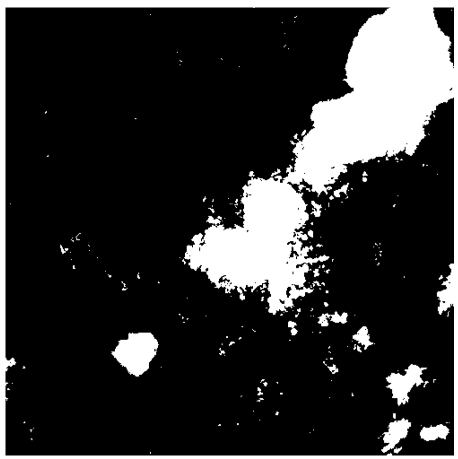

Band 2 (Green Band)

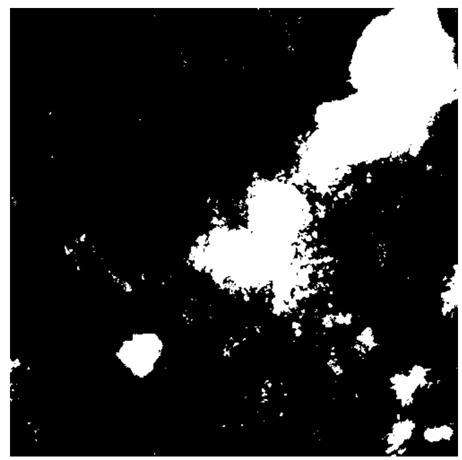

Band 3 (Red Band)

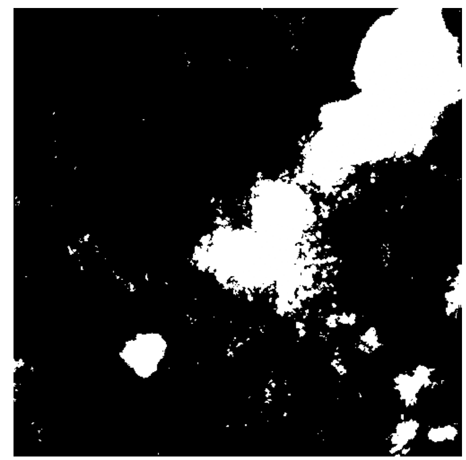

Band 4 (Near-IR Band)


Band 5 (Mid-IR Band)


Band 6 (Thermal IR Band)


Software/Reference Mask


Hardware Floating-Point Mask (Approximate Normalization)

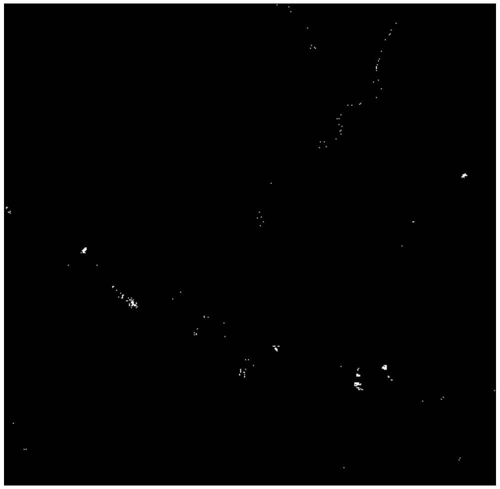

Hardware Fixed-Point Mask (Approximate Normalization)

Detection Accuracy (cnt'd)
(Approximate Normalization and Quantization Errors)

Approximation Error
(0.1028 %)

Hardware Floating-Point Error
(0.1028 %)

Hardware Fixed-Point (12-bit)
Error (0.2676 %)



Hardware Fixed-Point (23-bit)
Error (0.1028 %)

$$error = \frac{\sum_{i=0}^{(rows-1)} \sum_{j=0}^{(columns-1)} \left(\left| x_{ij} - y_{ij} \right| \right)}{rows \times columns},$$

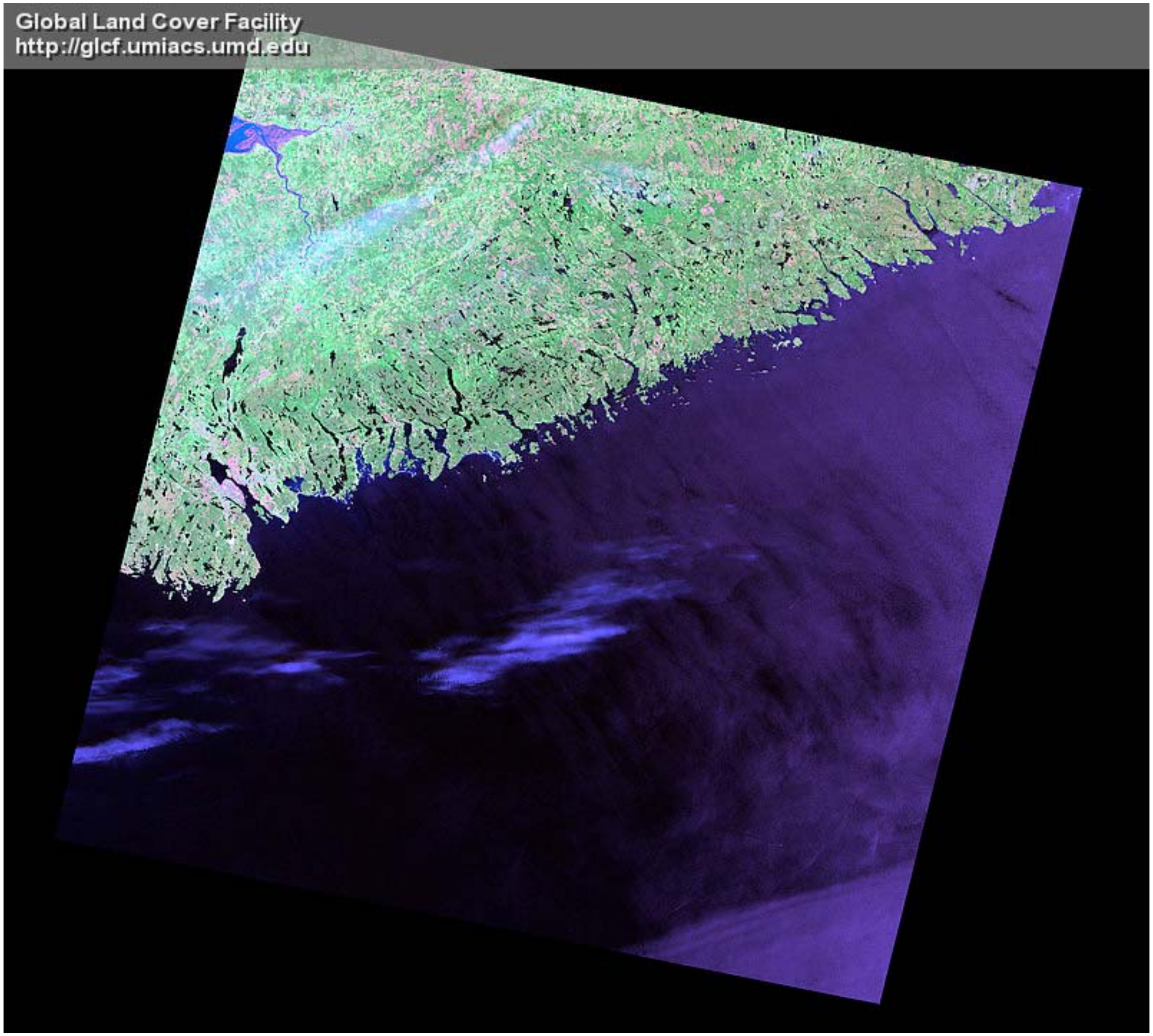
$where$

$x \equiv output\ \ image\ ,$

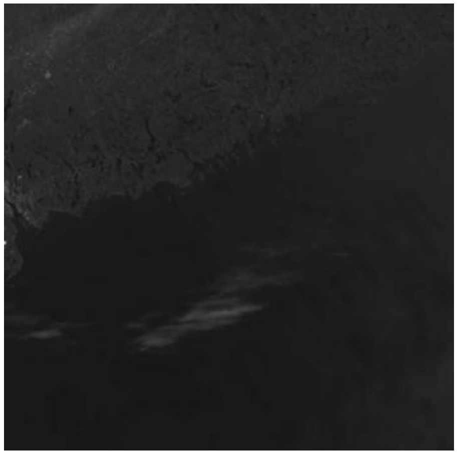
$y \equiv reference\ \ image$

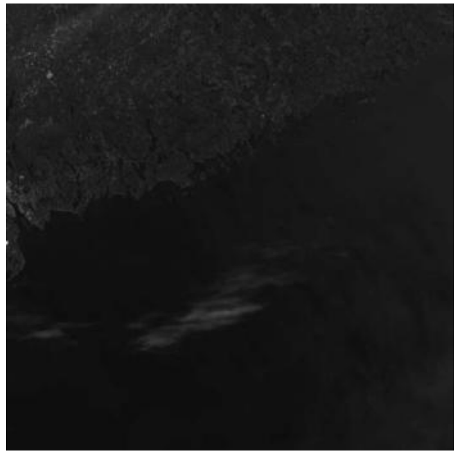
Reported Error (1.02 %)
by Williams et al. [2]

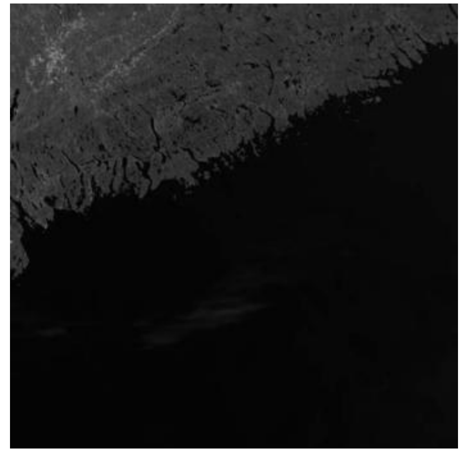
Detection Accuracy over Water

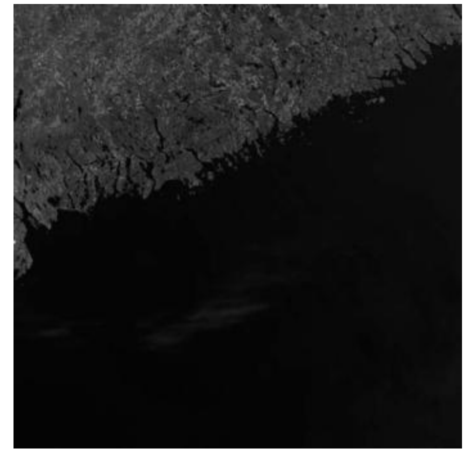


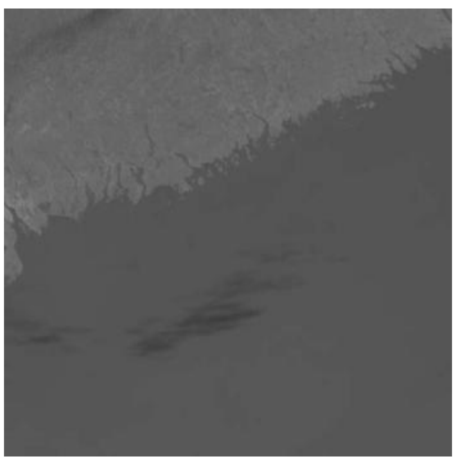
Detection Accuracy over Water
(Software/Reference Mask, Hardware Mask, Error Mask)


Band 2 (Green Band)


Band 3 (Red Band)

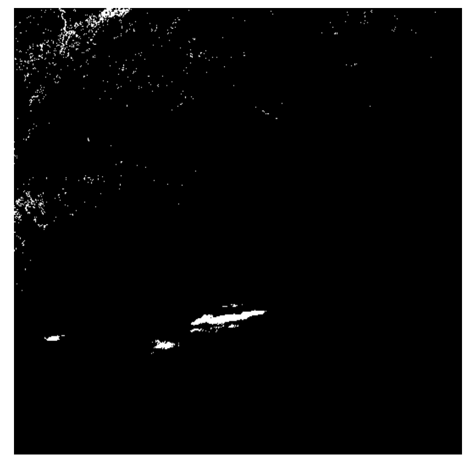

Band 4 (Near-IR Band)


Band 5 (Mid-IR Band)


Band 6 (Thermal IR Band)


Software/Reference Mask


Hardware Floating-Point Mask
(Approximate Normalization)


Approximation Error
(0.9102 %)

ACCA Resource Utilization

Platform	MAP Virtex II 6000
Speed	100 MHz
Slices	4,623 (13%)
LUTs	3,865 (5%)
Slice Flip Flops	8.023 (11%)
MULT 18X18	6 (4%)
RAMB16	6 (4%)

VHDL Fixed-Point (23-bit) of Pass-One

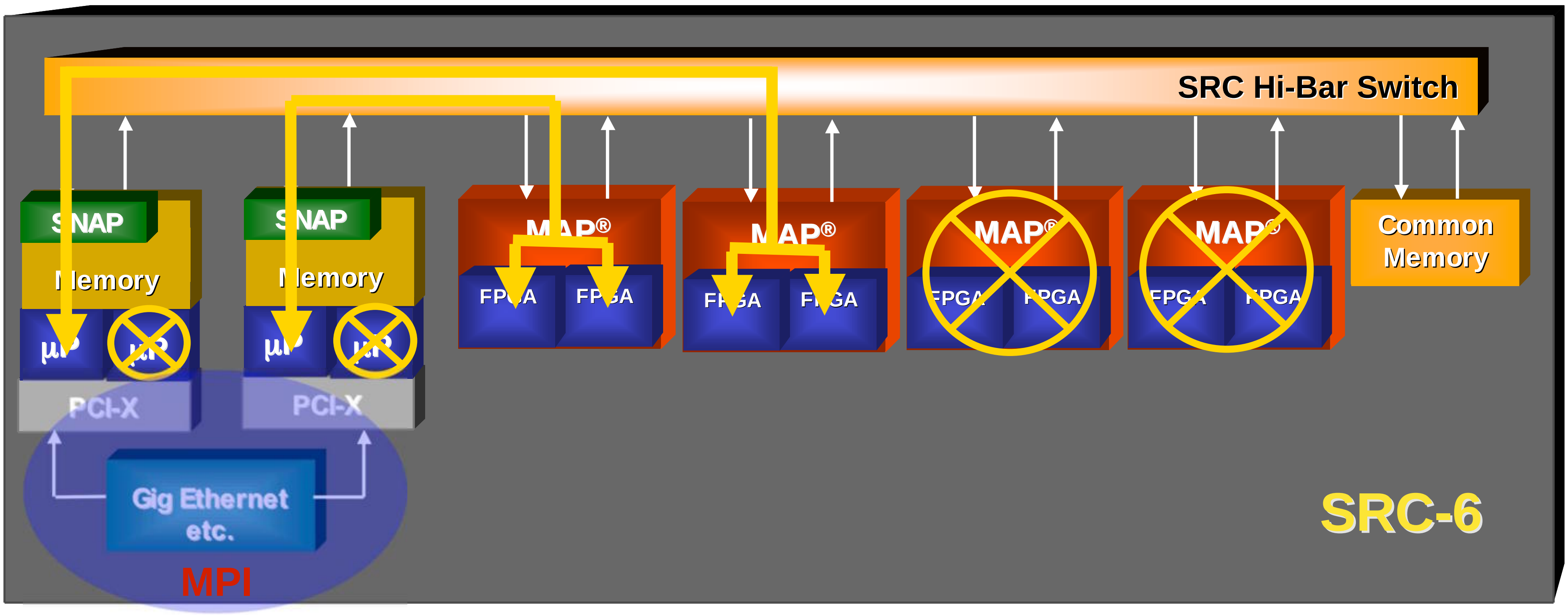
Platform	MAP Virtex-II 6000
Speed	100 MHz
Latency	78 Stages
Slices	17,565 (51%)
LUTs	20,885 (30%)
Slice Flip Flops	23,005 (34%)
MULT 18X18	36 (25%)

MAP-C Floating Point (Single-Precision) of Pass-One

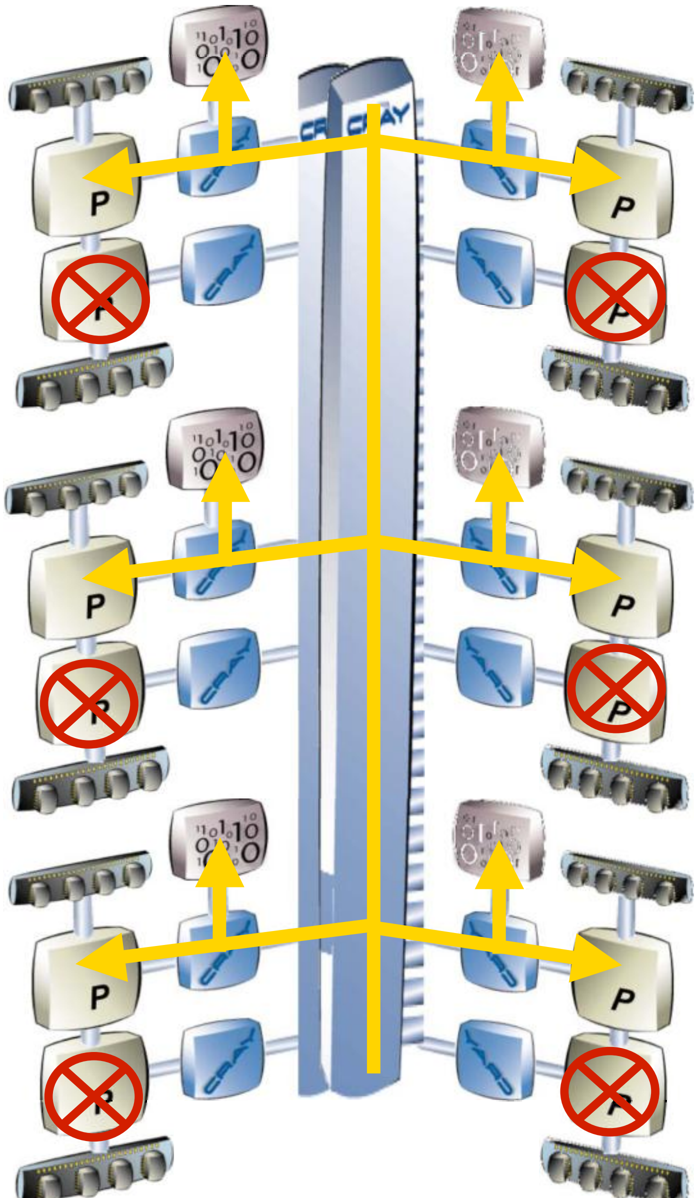
Platform	MAP Virtex-II 6000
Speed	100 MHz
Latency	1184 Stages
Slices	31,117 (92%)
LUTs	37,977 (56%)
Slice Flip Flops	40,584 (60%)
MULT 18X18	59 (40%)

MAP-C Floating Point of Pass-One & Partially Pass-Two

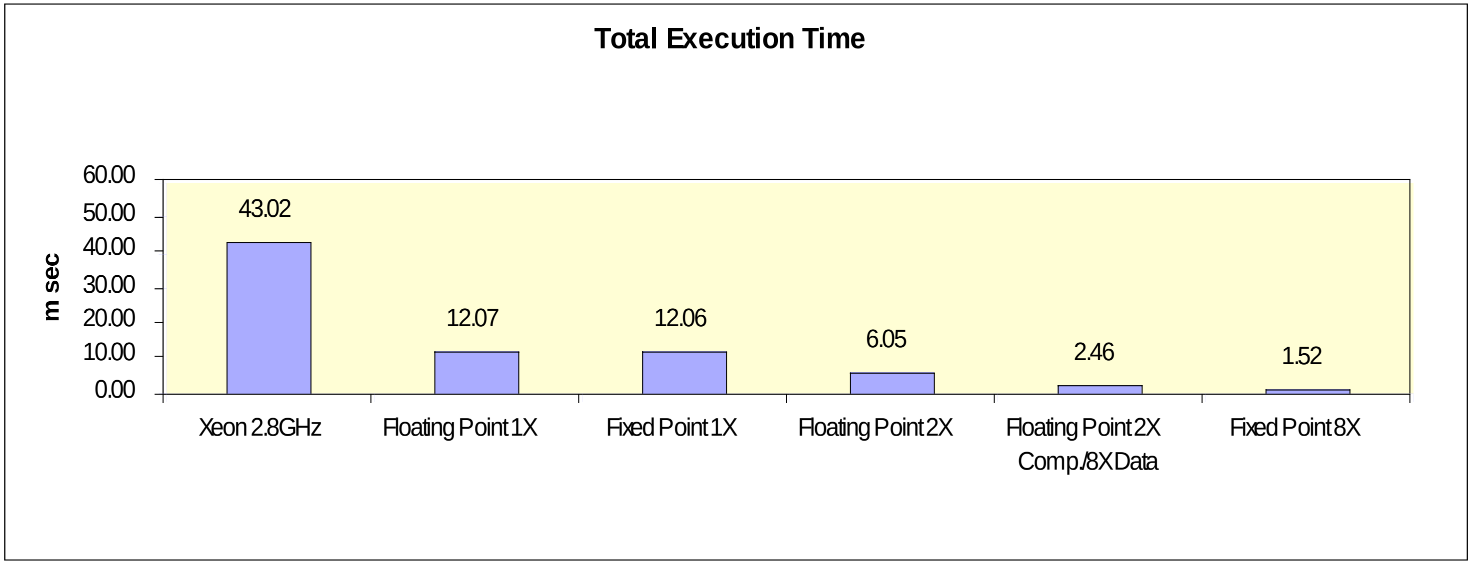
Multi-Node Measurements Scenarios on SRC-6

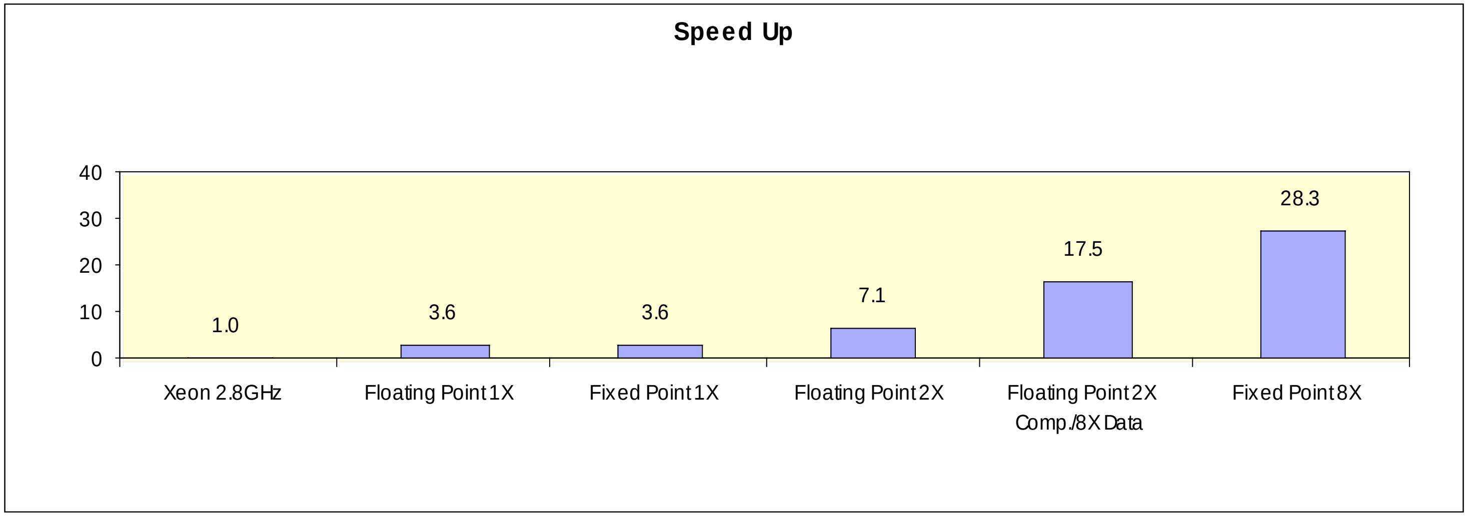


Multi-Node Measurements Scenarios on Cray-XD1



SRC-6 vs. Intel Xeon 2.8 GHz
(Hardware-to-Software Performance)





Multi-Node Execution Time

ACCA on SRC-6

Number of FPGAs	Processing Time (msec)		Communication Overhead (msec)
	1 Engine/Chip	8 Engines/Chip	
1	12.07	1.52	0
2	6.035	0.76	4.01
4	3.0175	0.38	4.2

ACCA on Cray-XD1

Number of Nodes	Processing Time (msec)		Communication Overhead (msec)
	1 Engine/Chip	8 Engines/Chip	
1	3.16	0.39	0
2	1.49	0.19	3.9
4	1.01	0.13	4.5
5	0.75	0.09	4.49
6	0.67	0.08	4.58

Concluding Remarks

- **We extended our previous effort [3] by:**
  - **Investigating the potential of using multi-node HPRCs for on-board preprocessing**
- **Landsat 7 ETM+ ACCA algorithm was selected to:**
  - **Determine an almost practical bounds on the potential performance of HPRCs**
  - **Gain an insight into the system level programmability and performance issues**
- **We studied and characterized the scalability of the application:**
  - **On two of the state-of-the-art reconfigurable platforms, SRC-6 and Cray-XD1 at HPCL/GWU**
- **The workload was distributed over all nodes using MPI:**
  - **We scattered the input five bands across all nodes, and**
  - **Gathered the resulting mask pixels from all nodes at the base node**

Concluding Remarks (cnt'd)

- The computation scalability on both machines was shown to be close to ideal
  - The communication overhead was almost constant irrespective of the number of nodes
  - The inherent parallelism of the application was fully exploited
- A deviation in the overall scalability from the ideal was observed and analyzed:
  - Overheads, such as communications, must be at a much lower levels than what is accepted in conventional high performance computers
- The results also showed that:
  - We may not need very large machines that are characterized with high overhead when HPRCs are used, which is a requirement for on-board preprocessing

References

[1] A. Michalski, K. Gaj, D.A. Buell, “High-Throughput Reconfigurable Computing: A Design Study of an IDEA Encryption Cryptosystem on the SRC-6e Reconfigurable Computer”, FPL 2005, pp.681-686.

[2] J.A. Williams, A.S. Dawood, S.J. Visser, “FPGA-based Cloud Detection for Real-Time Onboard Remote Sensing,” Proceedings of IEEE International Conference on Field-Programmable Technology (FPT 2002), 16-18 Dec. 2002, pp.110 – 116.

[3] E. El-Araby, M. Taher, T. El-Ghazawi, and J. Le Moigne, “Prototyping Automatic Cloud Cover Assessment (ACCA) Algorithm for Remote Sensing On-Board Processing on a Reconfigurable Computer”, IEEE International Conference on Field-Programmable Technology (FPT 2005), Singapore, 11-14 Dec., 2005.

[4] E. El-Araby, T. El-Ghazawi, J. Le Moigne, and K. Gaj, “Wavelet Spectral Dimension Reduction of Hyperspectral Imagery on a Reconfigurable Computer,” IEEE International Conference on Field-Programmable Technology, FPT 2004, Brisbane, Australia, December 2004.

[5] “SRC-6 C-Programming Environment Guide”, SRC Computers, Inc. 2005.

[6] “S-2433-131 Cray XD1TM Programming”, Cray Inc., Oct. 2005.

[7] “S-6400-131 Cray XD1TM FPGA Development”, Cray Inc., Oct. 2005.

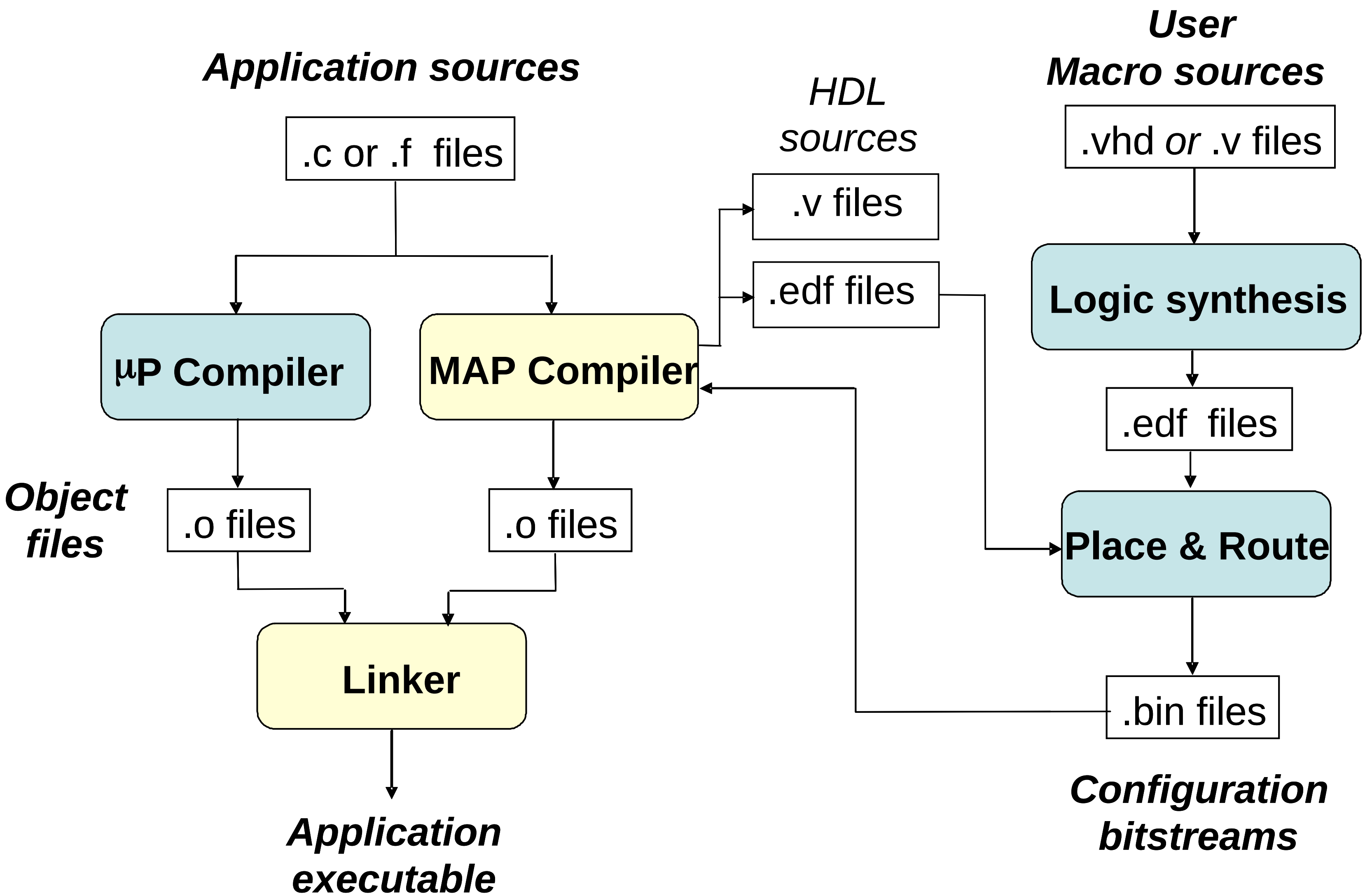
[8] R.R. Irish , “Landsat 7 Automatic Cloud Cover Assessment,” Algorithms for Multispectral, Hyperspectral and Ultraspectral Imagery VI, SPIE, Orlando, FL., USA, 24-26 April 2000, pp.348-355.

[9] J.A. Williams, A.S. Dawood, S.J. Visser, “Real-Time Wildfire and Volcanic Plume Detection from Spaceborne Platforms with Reconfigurable Logic,” 11th Australasian Remote Sensing and Photogrammetry Conference, Brisbane, Australia, 2-6 September 2002.

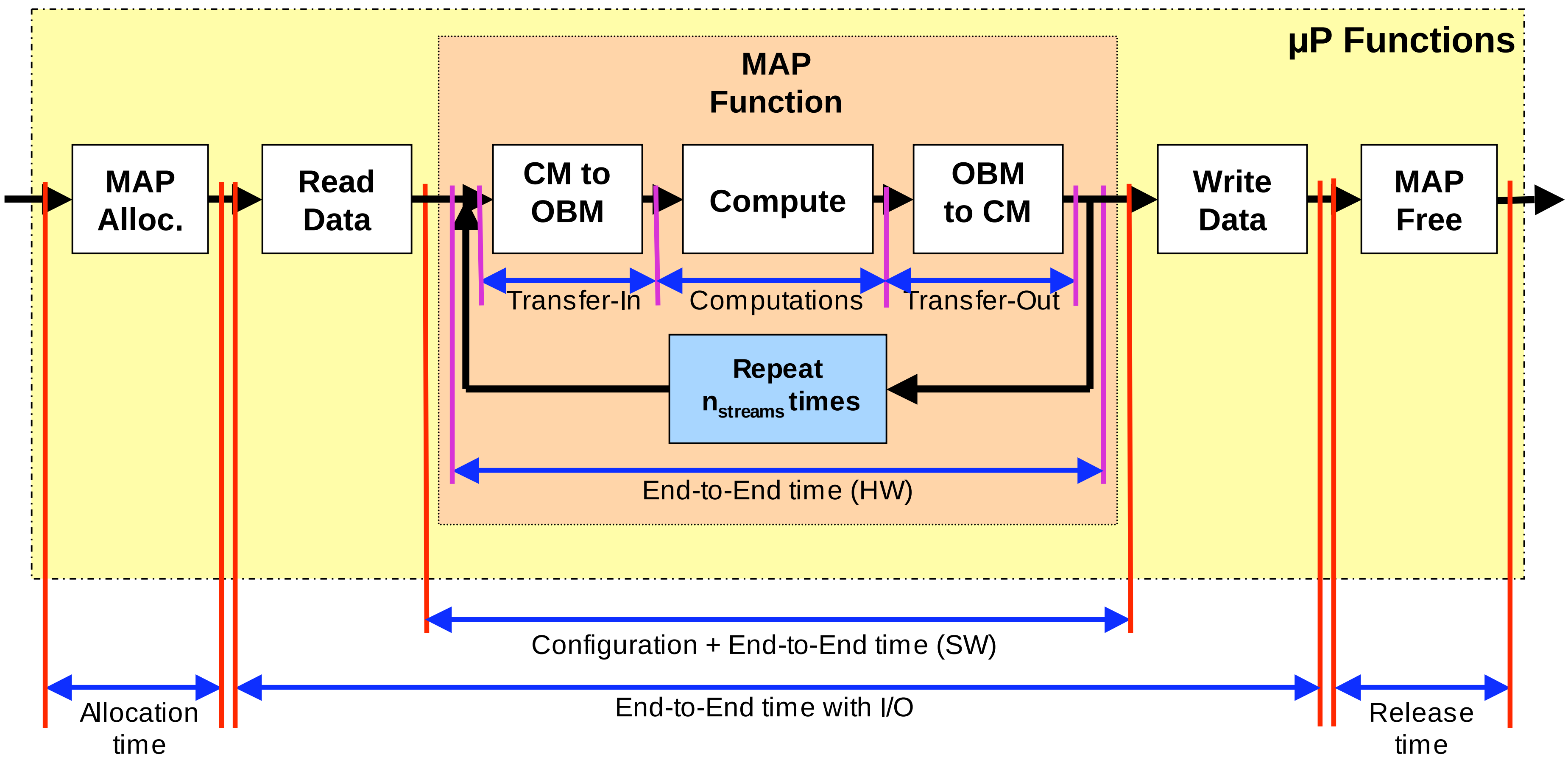
[10] R.S. Basso, J. Le Moigne, S. Veuella, and R.R. Irish, “FPGA Implementation for On-Board Cloud Detection,” International Geoscience and Remote Sensing Symposium. Hawaii, 20-24 July 2000.

Backup Slides

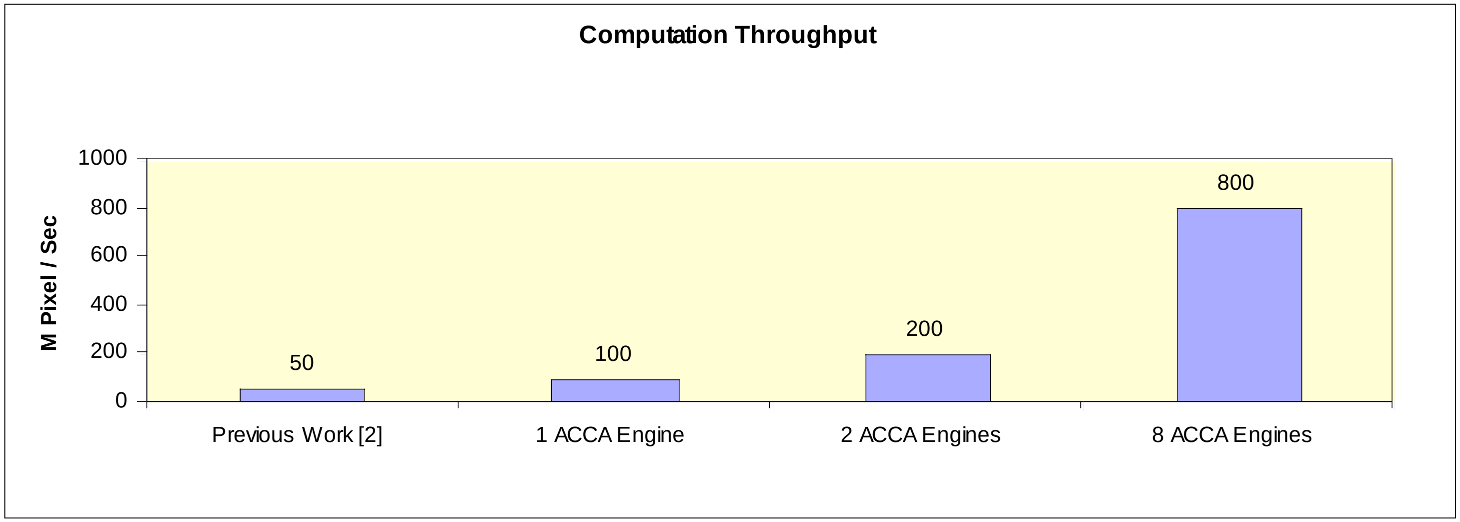
SRC Software Environment

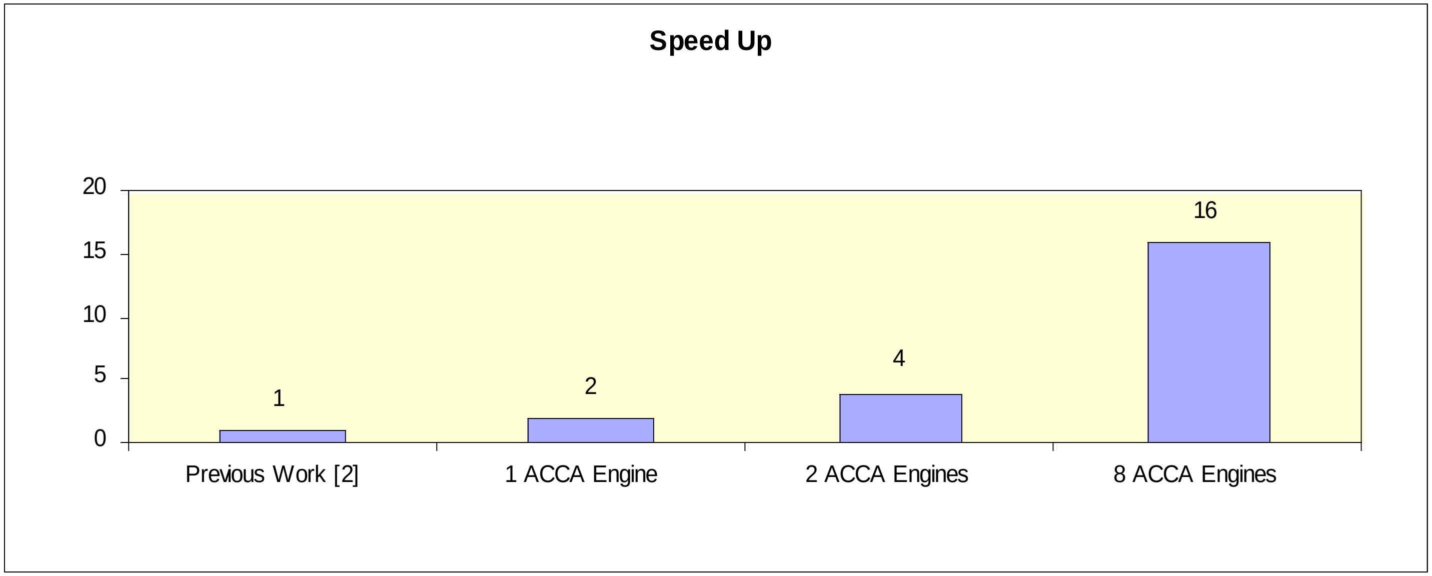


Single-Node Measurements Scenarios on SRC-6



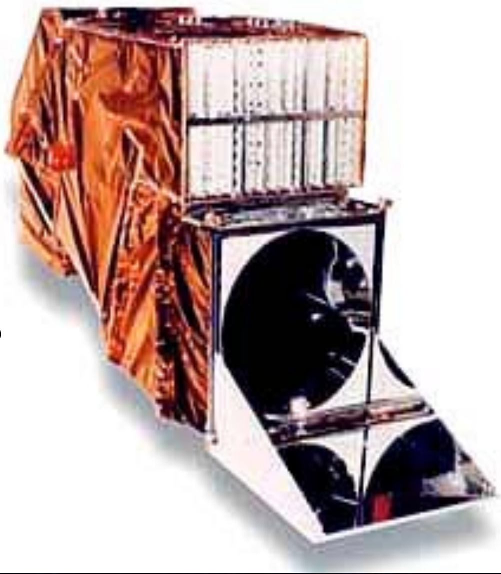
Hardware Computation Throughput
(Hardware-to-Hardware Performance)



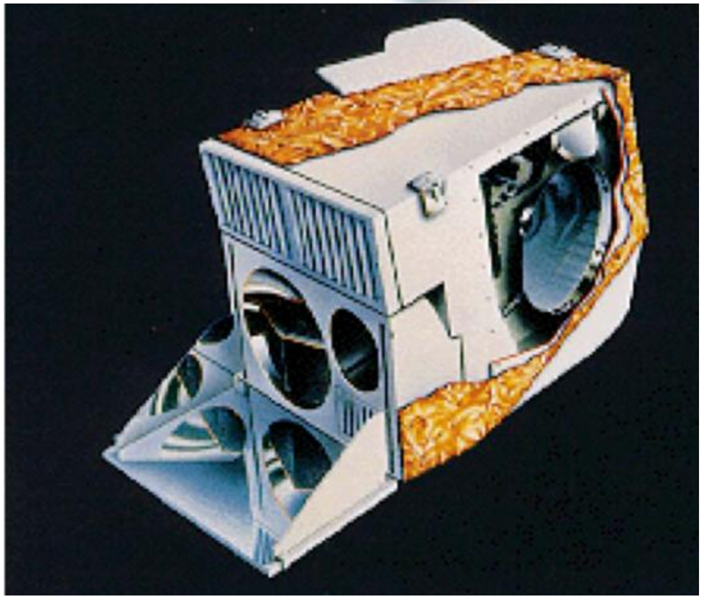


Cloud Detection: Example Satellites and Algorithms

Landsat 5



MODIS



ETM+

Optimizing Hardware Resources Usage
(Linearization of the Normalization Function)

$$\rho_i = \beta_i \times band_i + \alpha_i \ , \ \ i = 2,3,4,5,6$$

$$B_i = \rho_i \ , \ \ i = 2,3,4,5$$

$$B_6 = \frac{K_2}{\ln\left(\frac{K_1}{\rho_6}+1\right)} = \frac{K_2}{\ln\left(\frac{K_1}{\rho_6}\left(1+\frac{\rho_6}{K_1}\right)\right)} = \frac{K_2}{\ln\left(\frac{K_1}{\rho_6}\right)+\ln\left(1+\frac{\rho_6}{K_1}\right)} = \frac{K_2}{\ln(K_1)-\ln(\rho_6)+\ln\left(1+\frac{\rho_6}{K_1}\right)}$$

$$when \ |x|<1 \ \Rightarrow \ \ln(1+x) \cong x \ , \ \frac{1}{1-x} \cong 1+x$$

$$\because (0<\rho_6<1) \ and \ (K_1 >> 1) \Rightarrow 0 < \frac{\rho_6}{K_1} < 1 \Rightarrow \ln\left(1+\frac{\rho_6}{K_1}\right) \cong \frac{\rho_6}{K_1}$$

$$\therefore B_6 = \frac{K_2}{\ln(K_1)-\ln(\rho_6)+\ln\left(1+\frac{\rho_6}{K_1}\right)} = \frac{K_2}{\ln(K_1)-\ln(1+(\rho_6-1))+\ln\left(1+\frac{\rho_6}{K_1}\right)} \cong \frac{K_2}{\ln(K_1)-(\rho_6-1)+\frac{\rho_6}{K_1}}$$

Optimizing Hardware Resources Usage

(Linearization of the Normalization Function)

$$B_6 \cong \frac{K_2}{\ln(K_1)-(\rho_6-1)+\dfrac{\rho_6}{K_1}} \cong \frac{K_2}{1+\ln(K_1)-\rho_6+\dfrac{\rho_6}{K_1}} \cong \frac{K_2}{1+\ln(K_1)-\rho_6\left(1-\dfrac{1}{K_1}\right)} \cong \frac{K_2}{1+\ln(K_1)}\cdot\left(\frac{1}{1-\rho_6\cdot\dfrac{\left(1-\dfrac{1}{K_1}\right)}{1+\ln(K_1)}}\right)$$

$$\because (0<\rho_6<1) \; and \; (K_1>>1) \Rightarrow 0<\rho_6\cdot\frac{\left(1-\dfrac{1}{K_1}\right)}{1+\ln(K_1)}<1$$

$$\therefore B_6 \cong \frac{K_2}{1+\ln(K_1)}\cdot\left(\frac{1}{1-\rho_6\cdot\dfrac{\left(1-\dfrac{1}{K_1}\right)}{1+\ln(K_1)}}\right) \cong \frac{K_2}{1+\ln(K_1)}\cdot\left(1+\rho_6\cdot\frac{\left(1-\dfrac{1}{K_1}\right)}{1+\ln(K_1)}\right) \cong \frac{K_2}{1+\ln(K_1)}+\frac{K_2\cdot\left(1-\dfrac{1}{K_1}\right)}{(1+\ln(K_1))^2}\cdot\rho_6$$

Optimizing Hardware Resources Usage
(Linearization of the Normalization Function)

$$B_6 = \frac{K_2}{\ln\left(\frac{K_1}{\rho_6}+1\right)} \cong \frac{K_2}{1+\ln(K_1)} + \frac{K_2\left(1-\frac{1}{K_1}\right)}{\left(1+\ln(K_1)\right)^2} \times \rho_6$$

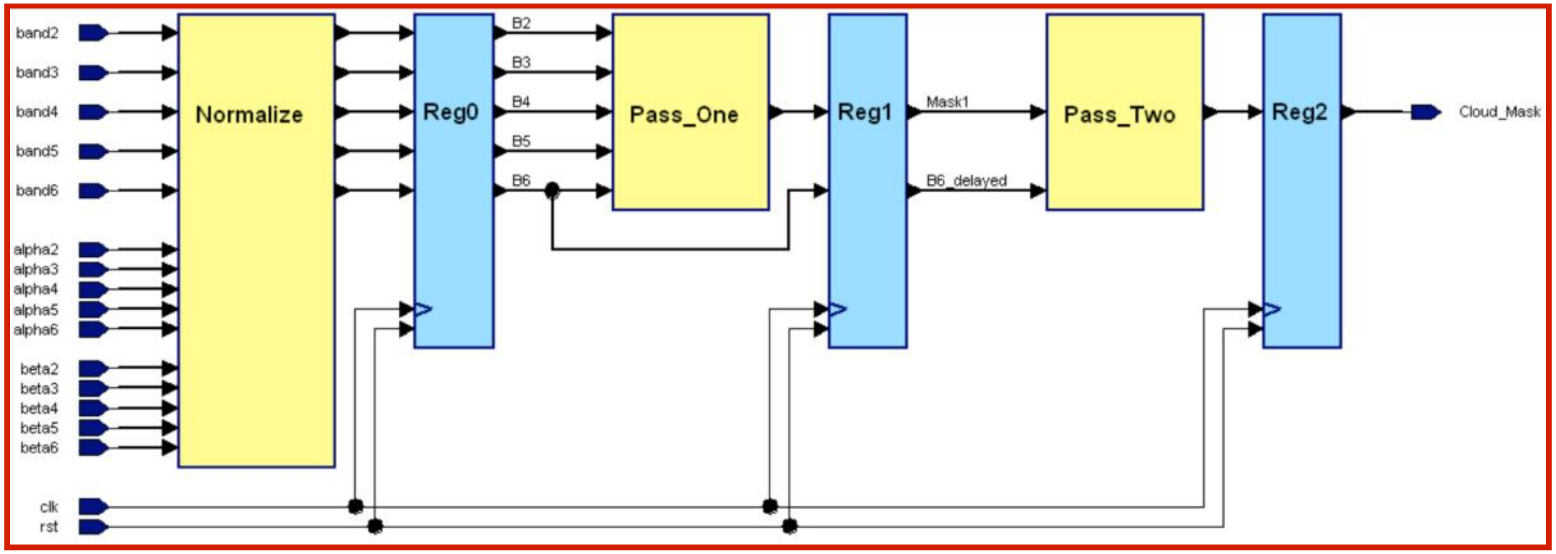
$$\because \rho_6 = \beta_6 \times band_6 + \alpha_6$$

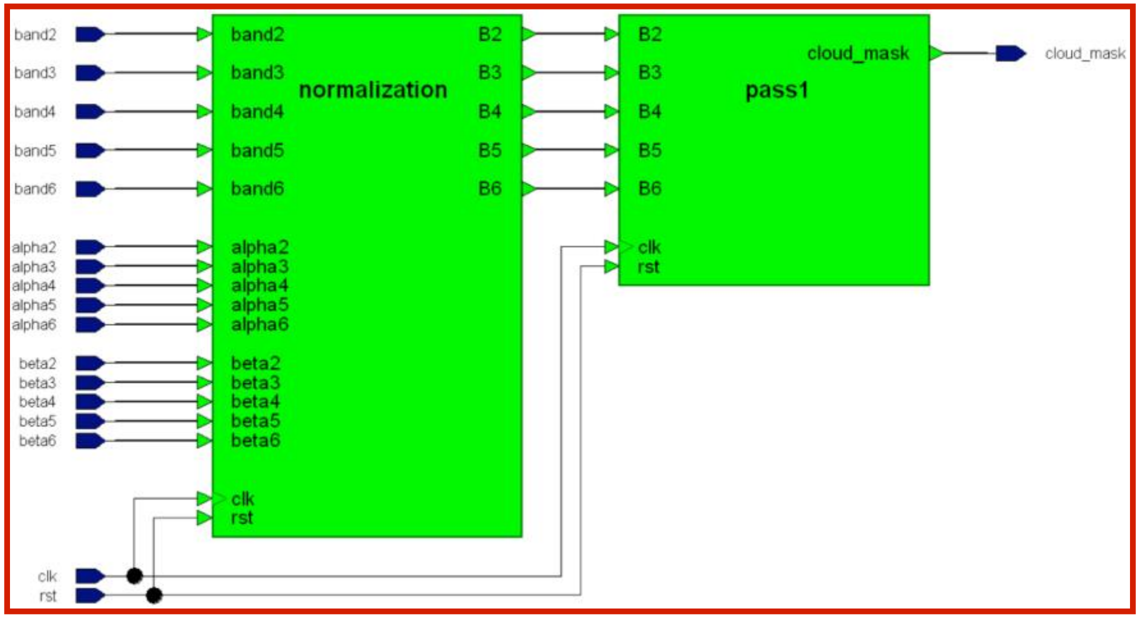
$$\therefore B_6 \cong \frac{K_2}{1+\ln(K_1)} + \frac{K_2\left(1-\frac{1}{K_1}\right)}{\left(1+\ln(K_1)\right)^2} \times \left(\beta_6 \times band_6 + \alpha_6\right)$$

$$B_6 \cong \left(\frac{K_2}{1+\ln(K_1)} + \frac{K_2\left(1-\frac{1}{K_1}\right)\cdot\alpha_6}{\left(1+\ln(K_1)\right)^2}\right) + \left(\frac{K_2\left(1-\frac{1}{K_1}\right)\cdot\beta_6}{\left(1+\ln(K_1)\right)^2}\right) \times band_6$$

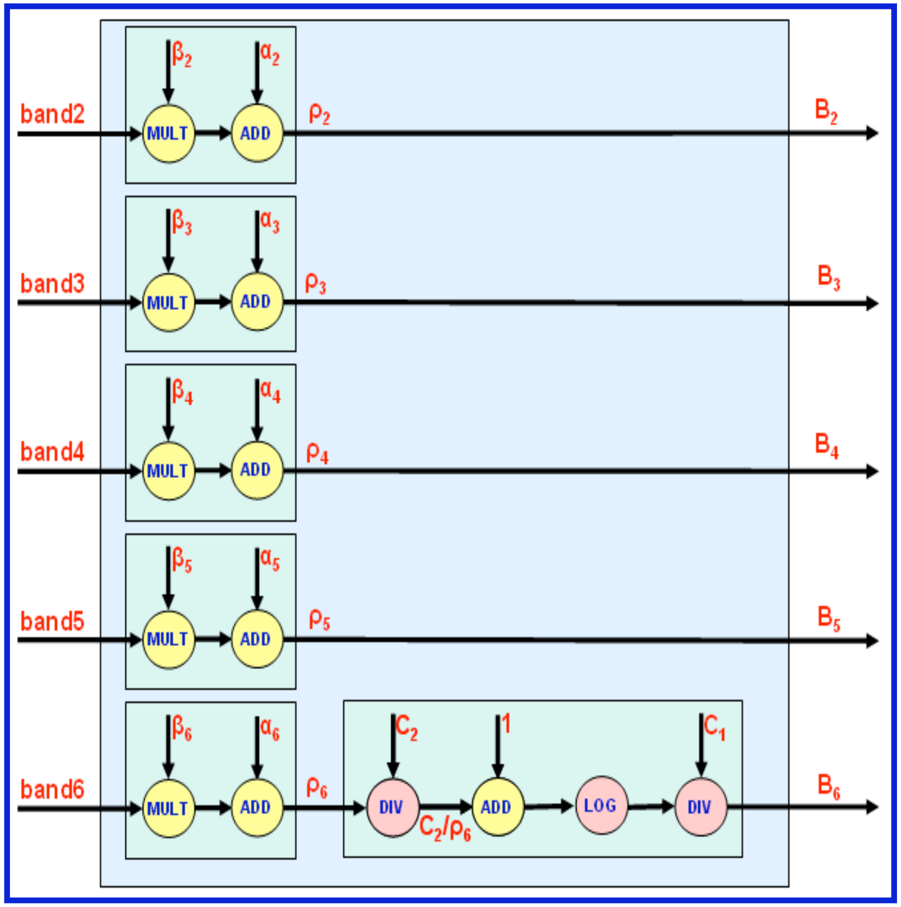
$$B_6 \cong \zeta + \delta \times band_6$$

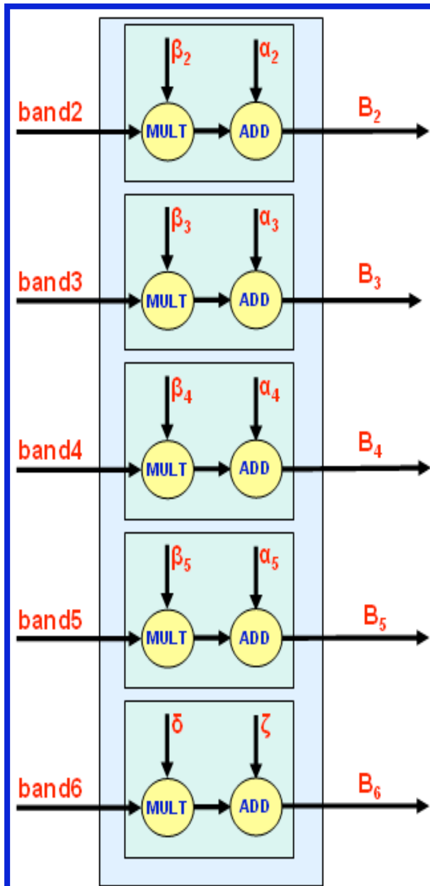
Top-Level Architecture of the ACCA Algorithm





Normalization Module





$$\rho_i = \beta_i \times band_i + \alpha_i \ , \ i = 2,3,4,5,6$$

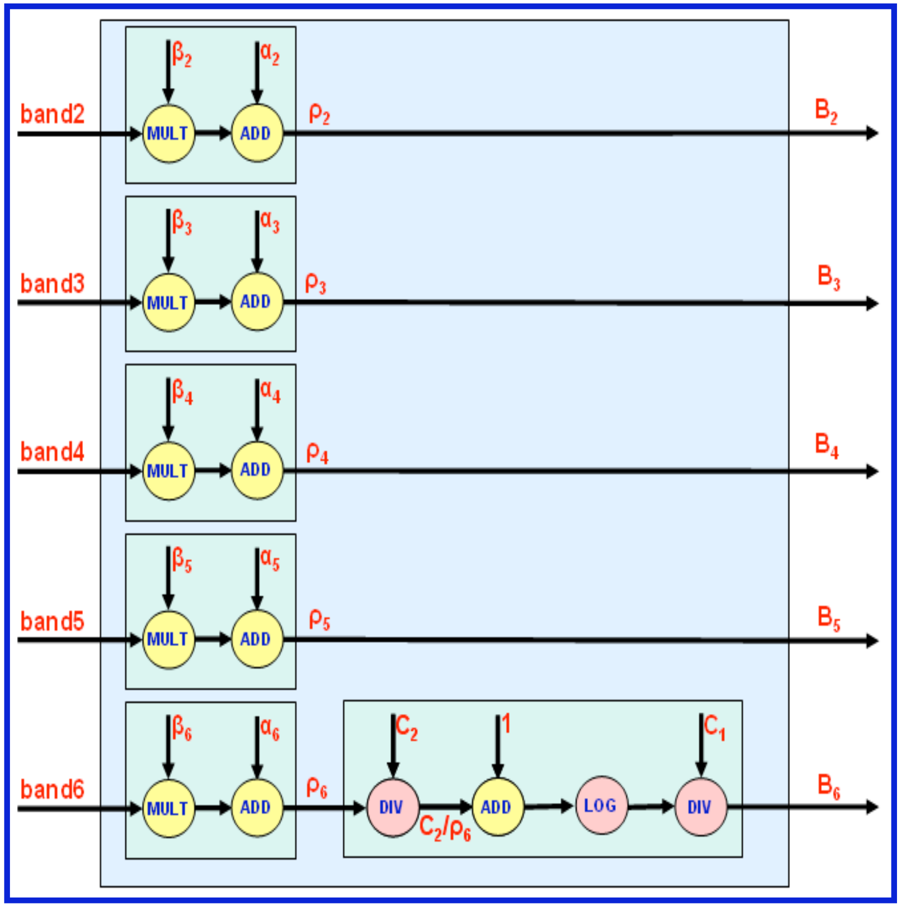
$$B_i = \rho_i \ , \ i = 2,3,4,5$$

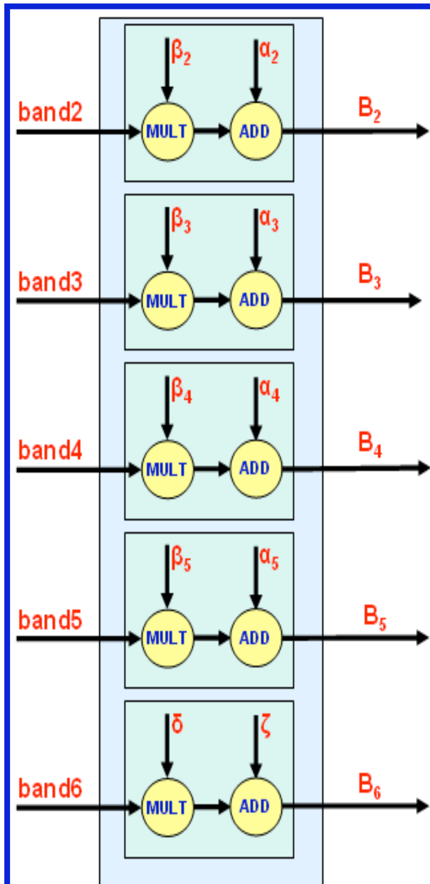
$$B_6 = \frac{C_1}{\log\left(\frac{C_2}{\rho_6}+1\right)} \cong \frac{C_1}{1+\log(C_2)} + \frac{C_1\left(1-\frac{1}{C_2}\right)}{\left(1+\log(C_2)\right)^2} \times \rho_6$$

$$B_6 \cong \frac{C_1 \cdot \alpha_6}{1+\log(C_2)} + \frac{C_1\left(1-\frac{1}{C_2}\right)\cdot \beta_6}{\left(1+\log(C_2)\right)^2} \times band_6$$

$$B_6 \cong \delta + \zeta \times band_6$$

Normalization Module





$$\rho_i = \beta_i \times band_i + \alpha_i \;,\quad i = 2,3,4,5,6$$

$$B_i = \rho_i \;,\quad i = 2,3,4,5$$

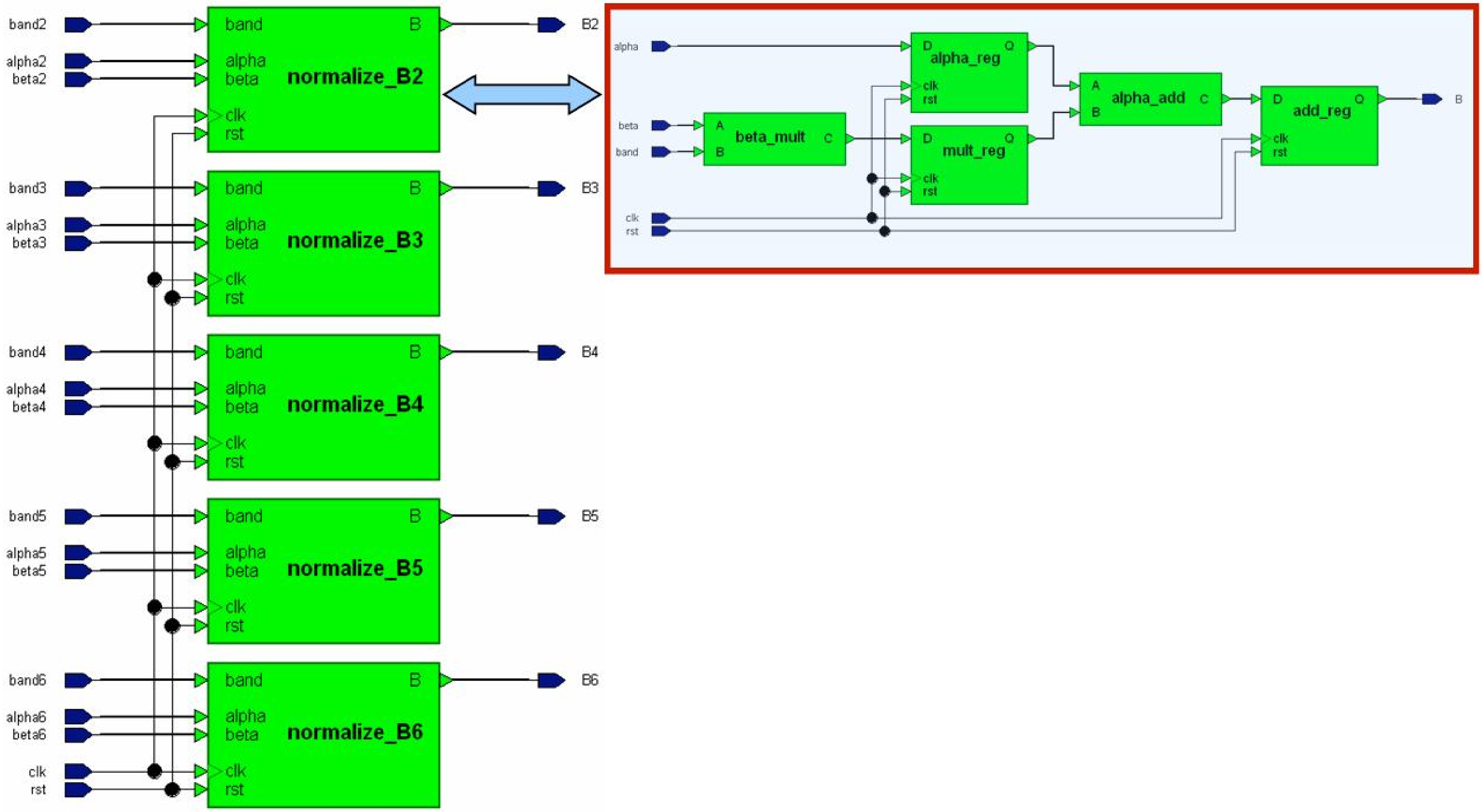
$$B_6 = \frac{K_2}{\ln\left(\frac{K_1}{\rho_6} + 1\right)}$$

$$B_6 \cong \frac{K_2}{1 + \ln(K_1)} + \frac{K_2\left(1 - \frac{1}{K_1}\right)}{(1 + \ln(K_1))^2} \times \rho_6$$

$$B_6 \cong \left\{ \begin{array}{l} \left(\frac{K_2}{1 + \ln(K_1)} + \frac{K_2\left(1 - \frac{1}{K_1}\right) \cdot \alpha_6}{(1 + \ln(K_1))^2} \right) + \\ \left(\frac{K_2\left(1 - \frac{1}{K_1}\right) \cdot \beta_6}{(1 + \ln(K_1))^2} \right) \times band_6 \end{array} \right.$$

$$B_6 \cong \zeta + \delta \times band_6$$

Normalization Module (cnt'd)

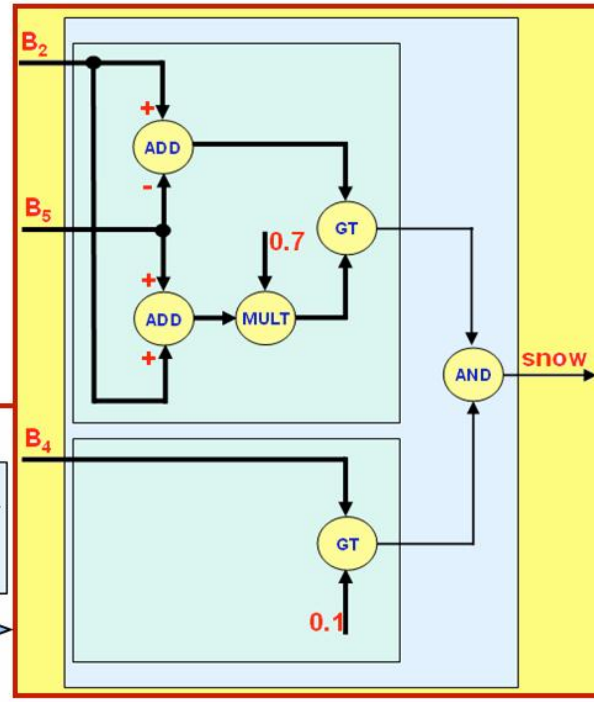


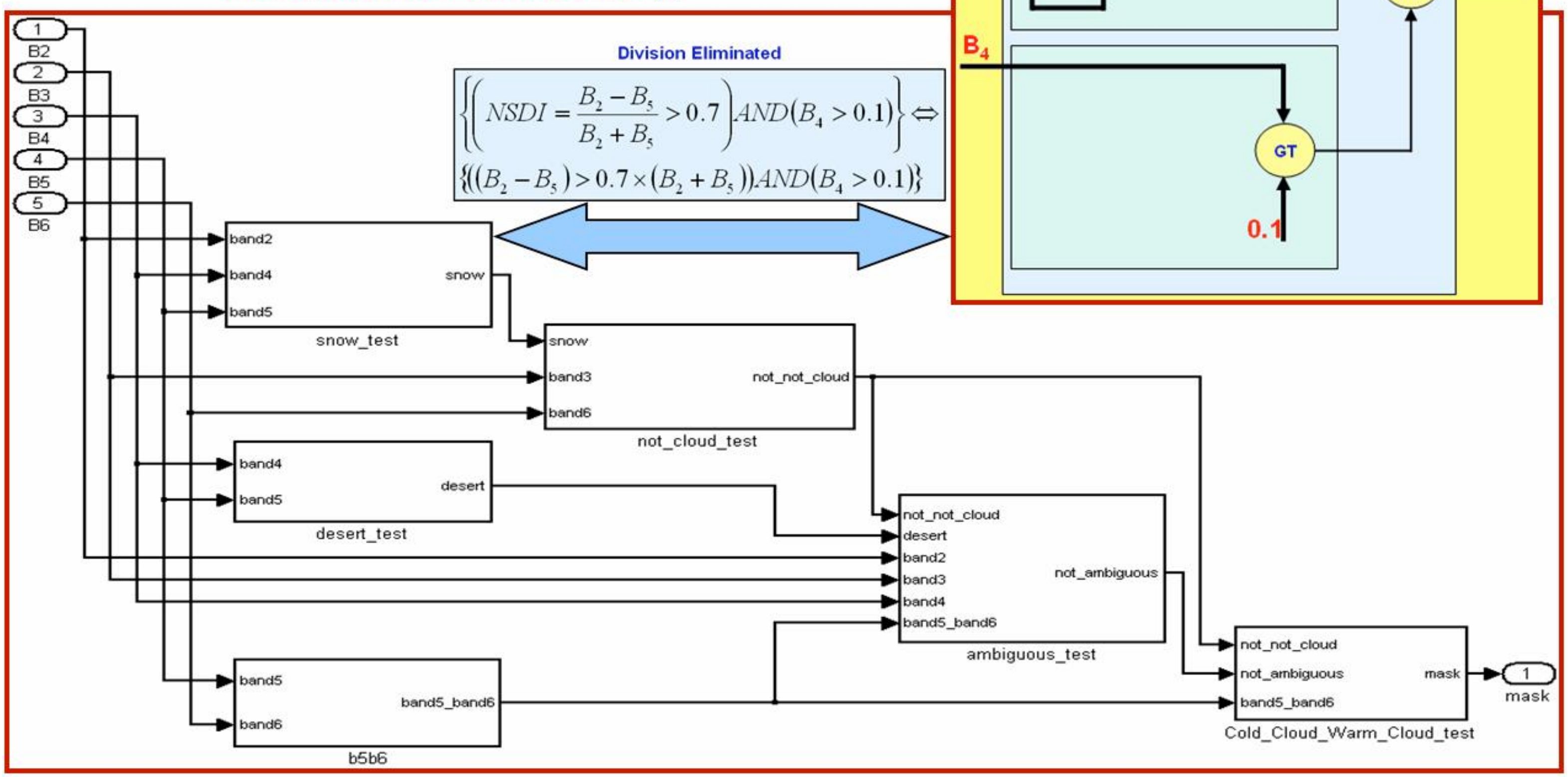
Pass-One Module

(Optimizing Hardware Resources Usage by Algebraic Re-Formulation)

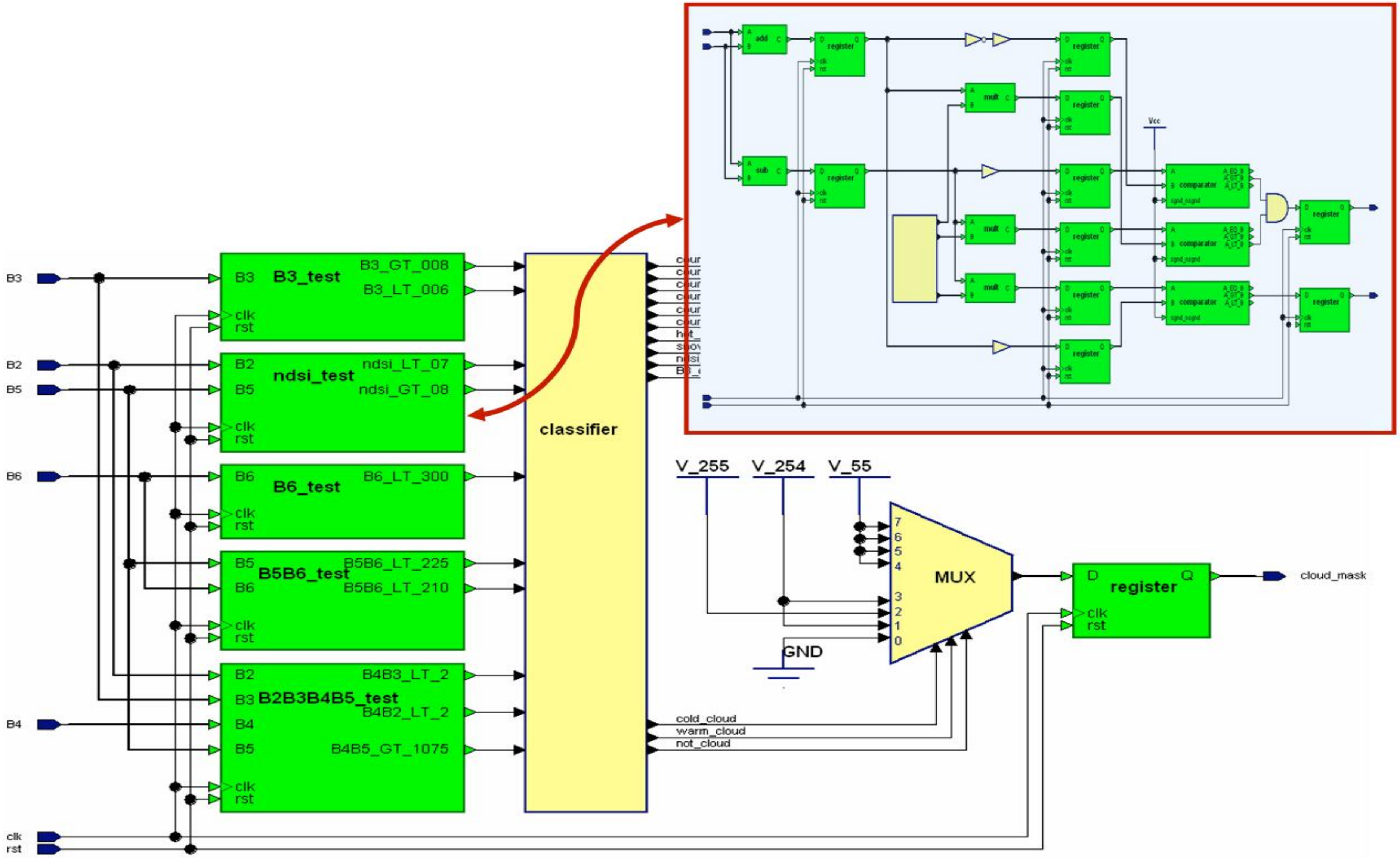
Classification	Rule
Snow	$\left(NSDI = \frac{B_2 - B_5}{B_2 + B_5} > 0.7\right) \ AND \ (B_4 > 0.1)^A$
Desert	$\frac{B_4}{B_5} < 0.83^B$
NotCloud	$(B_3 < 0.08) \ OR \ (B_6 > 300) \ OR \ (Snow)$
Ambiguous	$\left(((1-B_5)B_6 > 225) \ OR \left(\frac{B_4}{B_3} > 2\right) OR \left(\frac{B_4}{B_2} > 2\right) OR \ (Desert)\right) AND \ (\sim NotCloud)$
ColdCloud	$((1-B_5)B_6 \geq 210) \ AND \ (\sim Ambiguous) \ AND \ (\sim NotCloud)$
WarmCloud	$((1-B_5)B_6 < 210) \ AND \ (\sim Ambiguous) \ AND \ (\sim NotCloud)$

Classification Rules for Pass One [2]

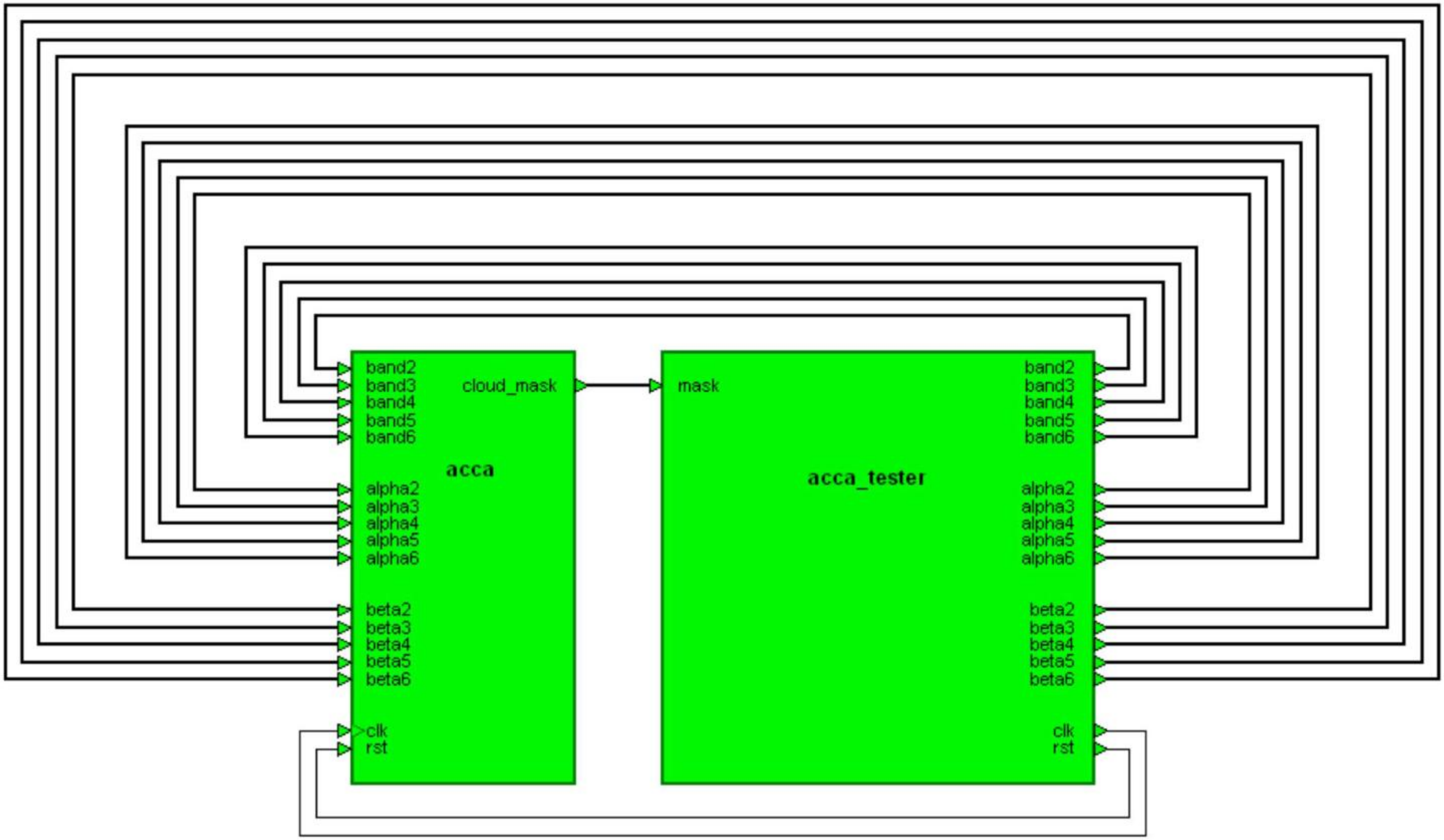




Pass-One Architecture



Test Bench


band2
band3
band4
band5
band6
cloud_mask
acca
alpha2
alpha3
alpha4
alpha5
alpha6
beta2
beta3
beta4
beta5
beta6
clk
rst
mask
acca_tester
band2
band3
band4
band5
band6
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alpha3
alpha4
alpha5
alpha6
beta2
beta3
beta4
beta5
beta6
clk
rst

Tester Architecture

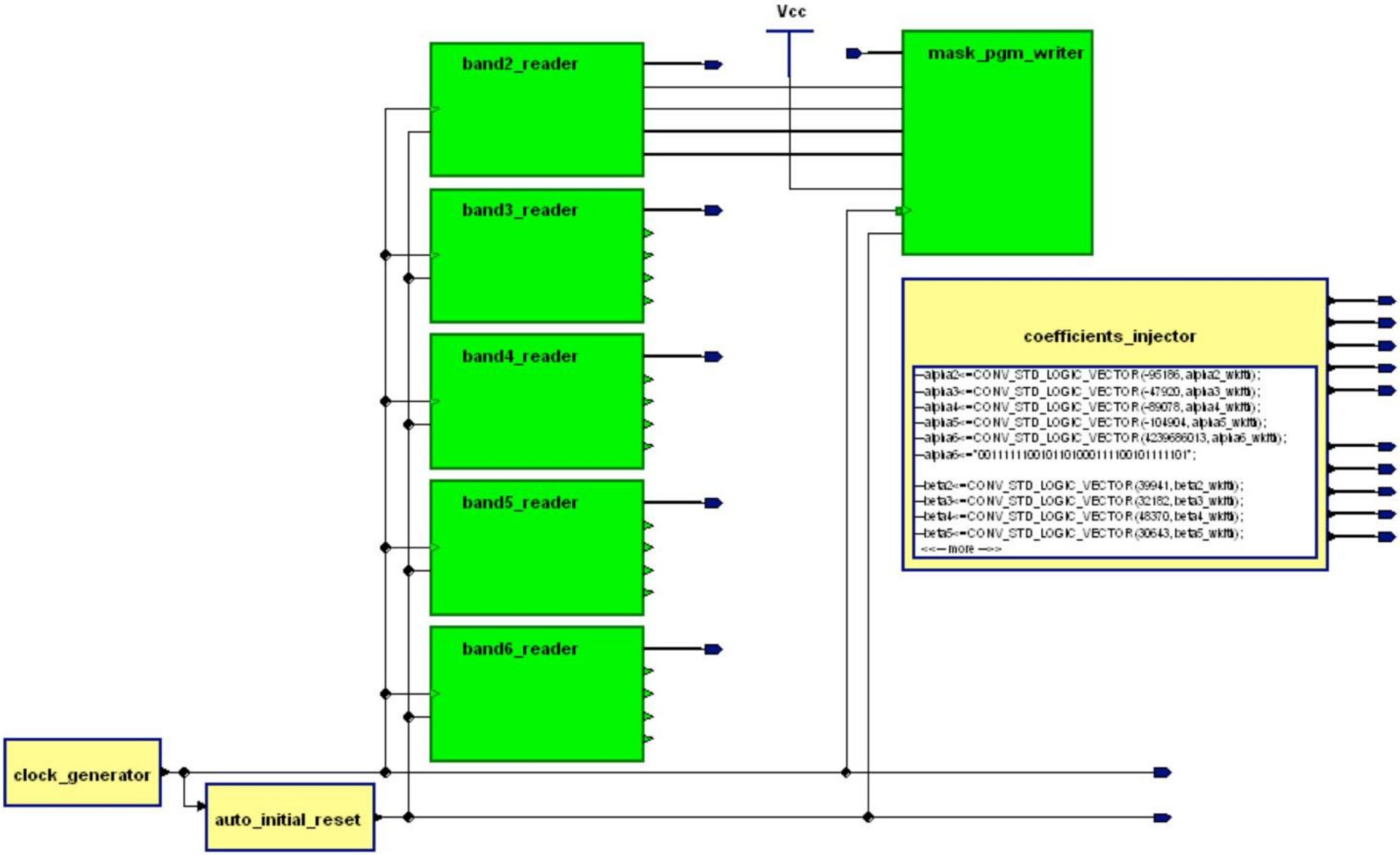

Image Reader and Writer